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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER NPRDC TR 84-51	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) HUMAN ENGINEERING DATA BASE FOR DESIGN AND SELECTION OF CATHODE RAY TUBE AND OTHER DISPLAY SYSTEMS		5. TYPE OF REPORT & PERIOD COVERED Technical Report Sep 1982-Jun 1984
		6. PERFORMING ORG. REPORT NUMBER 71-84-1
7. AUTHOR(s) D. Meister		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Navy Personnel Research and Development Center San Diego, California 92152		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 525-001-028.03.01
11. CONTROLLING OFFICE NAME AND ADDRESS Navy Personnel Research and Development Center San Diego, California 92152		12. REPORT DATE July 1984
		13. NUMBER OF PAGES 362
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Human engineering
Displays
Operator performance

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The literature dealing with operator performance in using electronic displays has been compiled to serve as a human performance data base and guide for the design of new Navy systems.

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FOREWORD

This guide is intended to serve as a source of basic data for display engineers on human capabilities and performance as related to the visual display characteristics of CRT and other displays. Its primary purpose is to acquaint visual display engineers with what is currently known about the relation between observer characteristics and various types of display applications. The reader is assumed to have a knowledge of the engineering fundamentals and scientific principles related to display design; hence, no detailed discussion of these matters is provided.

The presentation is based on earlier effort by Meister and Sullivan (1969). The material is presented in as succinct and explicit a manner as possible with discussions limited to the substance of the particular problem or subject. Where recommendations are offered, they tend to represent the level that will optimize <u>human performance</u> in the system.

This work was performed under work unit 525-001-028.03.01 (Human Factors Engineering Data Base Development) under the sponsorship of Naval Sea System Command.

The invaluable assistance of Dr. Herschel C. Self of the Visual Display Systems Branch (AFAMRL/HEA) of the Air Force Aerospace Medical Research Laboratory, Ronald A. Erickson of the U.S. Naval Weapons Center, and Ed Rizy of Submarine Signal Division, Raytheon, in critiquing the draft manuscript is gratefully acknowledged.

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NPRDC TR 84-51

JULY 1984

HUMAN ENGINEERING DATA BASE FOR DESIGN AND SELECTION OF CATHODE RAY TUBE AND OTHER DISPLAY SYSTEMS

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NAVY PERSONNEL RESEARCH
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NPRDC TR 84-51 July 1984

HUMAN ENGINEERING DATA BASE FOR DESIGN AND SELECTION OF CATHODE RAY TUBE AND OTHER DISPLAY SYSTEMS

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SUMMARY

Problem

Many major Navy systems are developed without the aid of human factors engineering (HFE) advice and data. As a result, these systems are difficult to operate, are prone to personnel error, and have reduced operational effectiveness. One of the reasons project managers and design engineers are reluctant to utilize HFE inputs is that they do not have ready access to HFE data in a simple format suitable for the nonspecialist.

Objective

The overall objective of the project for which this guide was developed is to create an HFE data retrieval support system for managers and designers that will facilitate their use of HFE data. The objective of this guide is to provide this HFE data retrieval support system in the area of cathode ray tube (CRT) and advanced display systems.

Approach

The relevant display literature from around 1944 to the present was reviewed. Available human performance data and information on factors affecting human performance with CRT and advanced electronic displays (e.g., forward looking infrared radar, low-light level TV, plasma displays) were extracted from the literature and reformatted to satisfy the needs of managers, designers, and HFE specialists.

Findings

This handbook updates the available human performance data relevant to CRT and advanced displays in the following areas:

Section 1. Introduction and Approach to Display Design and Selection.
Section 2. Visual Display Parameters.
Section 3. CRT Display Systems: Plan-Position-Indicator (PPI) Displays.
Section 4. CRT Display Systems: Television Displays.
Section 5. Selection of New Display Technologies.
Section 6. Target Acquisition Imaging Systems.
Section 7. Matrix Displays.
Section 8. Coding of Symbols.
Section 9. Environmental Effects.
Section 10. Operational Performance Data.

Conclusions and Recommendations

The present volume is a compendium of human performance data on electronic displays. It is recommended that this volume be provided managers and designers in all system development or acquisition projects making use of such displays.

CONTENTS

SECTION 1

INTRODUCTION AND APPROACH TO DISPLAY DESIGN AND SELECTION

1.0 INTRODUCTION AND APPROACH TO DISPLAY DESIGN AND SELECTION

1.1 Purpose

The purpose of this data base is to supply display engineers and project managers with basic data describing human capabilities and performance in relation to cathode ray tube (CRT) and new display systems.

1.2 Approach to Display Design

In specifying the display characteristics for a particular system application, it is assumed that certain basic system decisions have already been made. For example, after the system objectives, system functions, man-machine tasks, human operation information and control requirements, and display system design concepts have been established, the detailed definition of the physical characteristics of the display are still needed.

Many display characteristics affect operator performance; some are more important than others. Meister and Sullivan (1969) felt that the following eight characteristics that apply only to CRTs are critically important:

a. Frame rate.
b. Contrast ratio.
c. Ambient illumination.
d. Target/symbol size.
e. Resolution.
f. Bandwidth.
g. Registration.
h. Phosphor type.

These characteristics will be discussed in greater detail. Other parameters that have an effect (however small) on operator performance, which will also be discussed in subsequent sections, are type of display (e.g., FLIR, LLLTV), display size and shape, screen color and brightness, stimulus number and density, number of individual displays to be monitored, frequency of stimulus presentation, character line spacing and luminance, stroke height/width ratio, character font and color, image polarity, viewing distance, percent active area, and screen orientation. All terms are defined in Section 2.

The exact priority of each parameter and the specific result of their interrelationships is a function of the individual display application. The relationships described herein are generalized models; the engineer must make appropriate substitutions for his particular situation. An approach to display selection in which the displays being considered are the more advanced types is presented in Section 5.

1.2.1 Display Design--Single Viewer Case

1.2.1.1 Frame Rate. The determination of frame rate, refresh rate, or regeneration rate for a given display is probably the most important aspect of display design in today's computer-linked display systems. Frame rate for a given display is a function of the following (see Figure 1):

a. Volume of information per frame.
b. Ambient illumination.

c. Phosphor.
d. System storage capacity.
e. System write/erase speed.
f. Bandwidth.
g. Display control techniques.

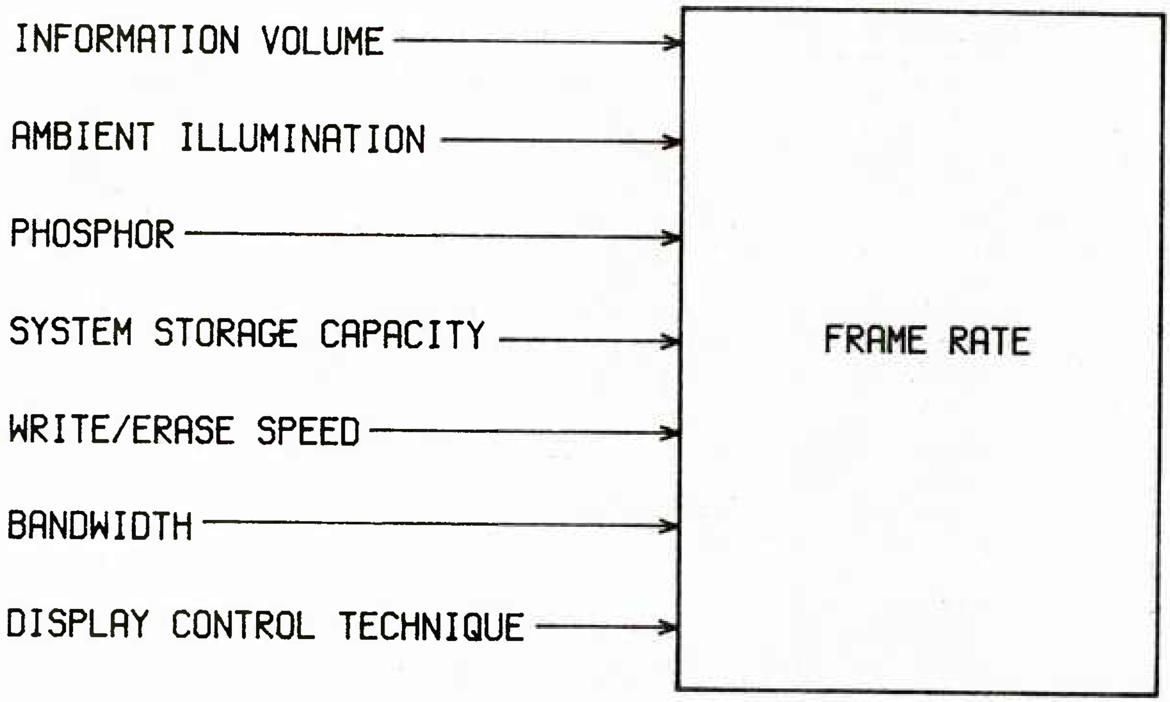


Figure 1. Factors affecting frame rate.

Conversely, specifying a particular frame rate directly affects the following (see Figure 2):

a. Flicker (the presence or absence of).
b. Bandwidth.
c. Resolution.
d. Phosphor.

It <u>indirectly</u> affects the following:

a. Ambient illumination.
b. Display brightness.

In practice, where information density is not high, phosphor is the main determinant of frame rate; where information density is high, the storage capacity and system write/erase speed limit frame rate.

Frame rate is an important consideration from the human factors point of view because it is the primary determinant of whether or not flicker (see paragraph 2.1.j) occurs. The effect of flicker upon the observer can range from distracting through annoying to actually debilitating. The critical flicker frequency (CFF) for a given display is set by the frame rate of the display, but the effect of frame rate can be attenuated to a certain extent by the control of ambient illumination and/or display brightness.

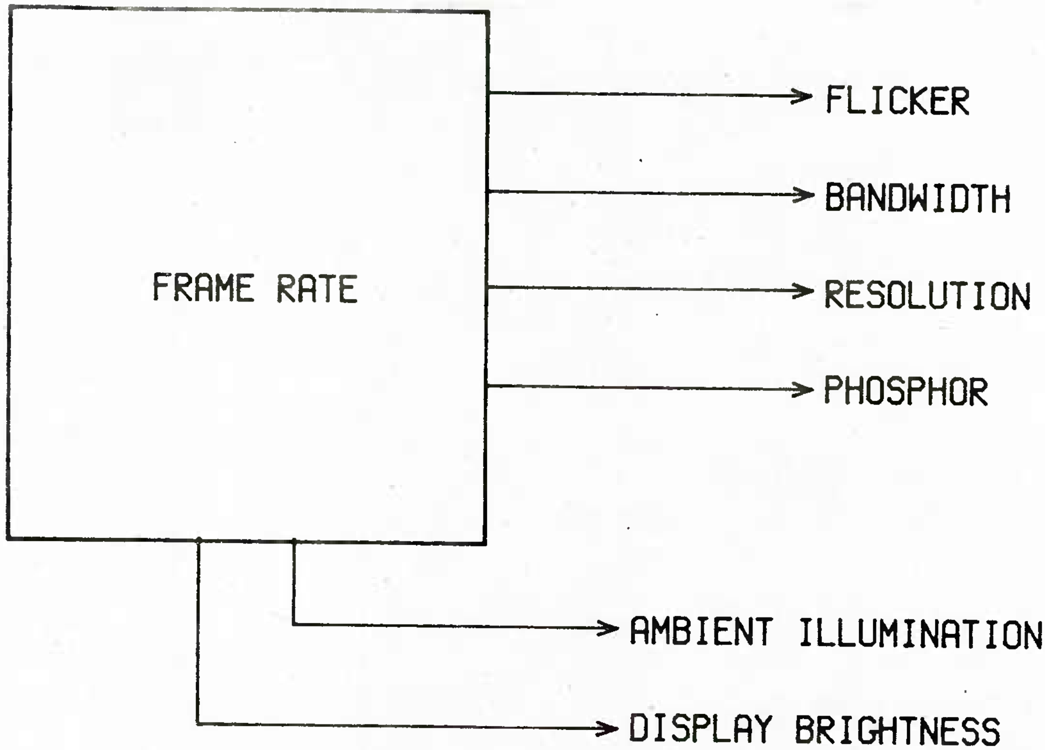


Figure 2. Factors directly affected by a specific frame rate.

1.2.1.2 Contrast Ratio and Ambient Illumination. The establishment of the optimum contrast ratio for a given display is irrevocably linked to the ambient illumination in which the display will operate. Although the range of brightness over which the human eye adapts is very large, perhaps 200:1, the minimum contrast ratio required for the operational discrimination of two adjoining areas on a display is about 2:1 (Bryden, 1969). Military standards normally specify 10:1 as the minimum acceptable contrast ratio.

Contrast ratio and ambient illumination are affected by the following (see Figure 3):

a. Display brightness
b. Symbol brightness
c. Ambient brightness
d. Phosphor

(a–d) and their interrelationships.

e. Type and nature of ambient light source.
f. Viewing geometry.
g. Presence or absence of shields, filters, etc.

In turn, these factors have a direct effect upon (see Figure 4):

a. Resolution.
b. Phosphor.
c. Display brightness.
d. Viewing geometry.

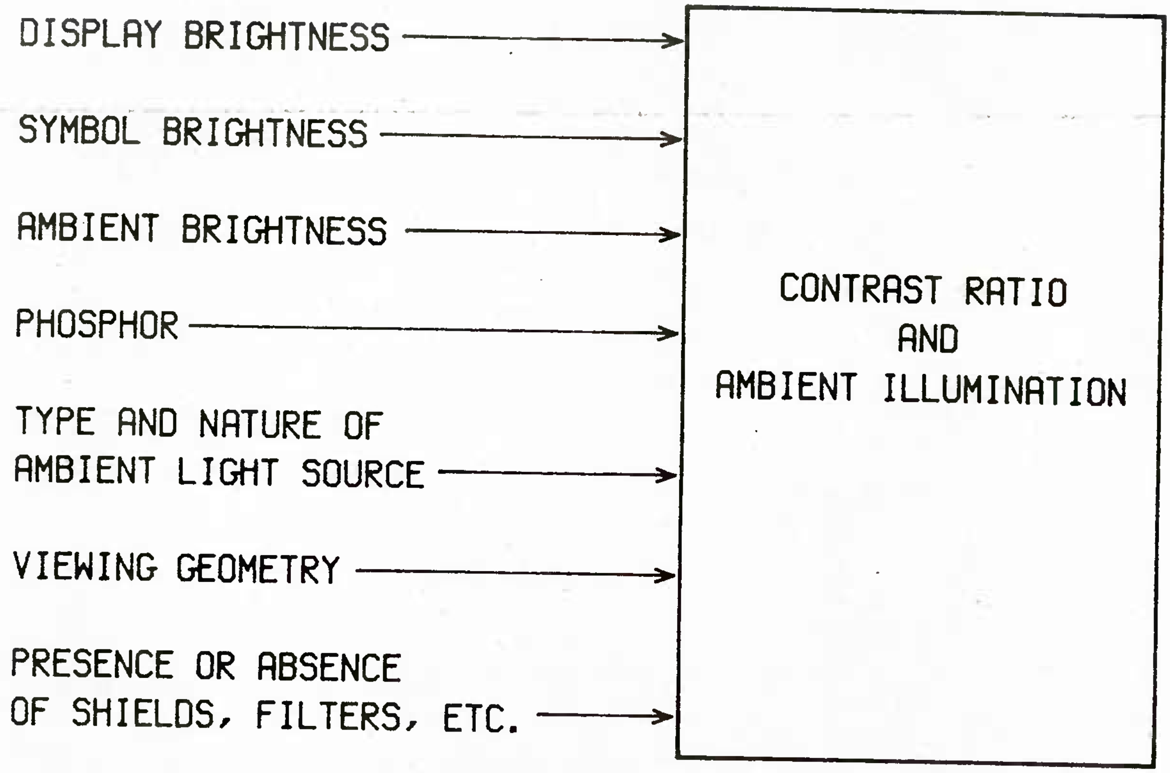


Figure 3. Factors affecting contrast ratio and ambient illumination.

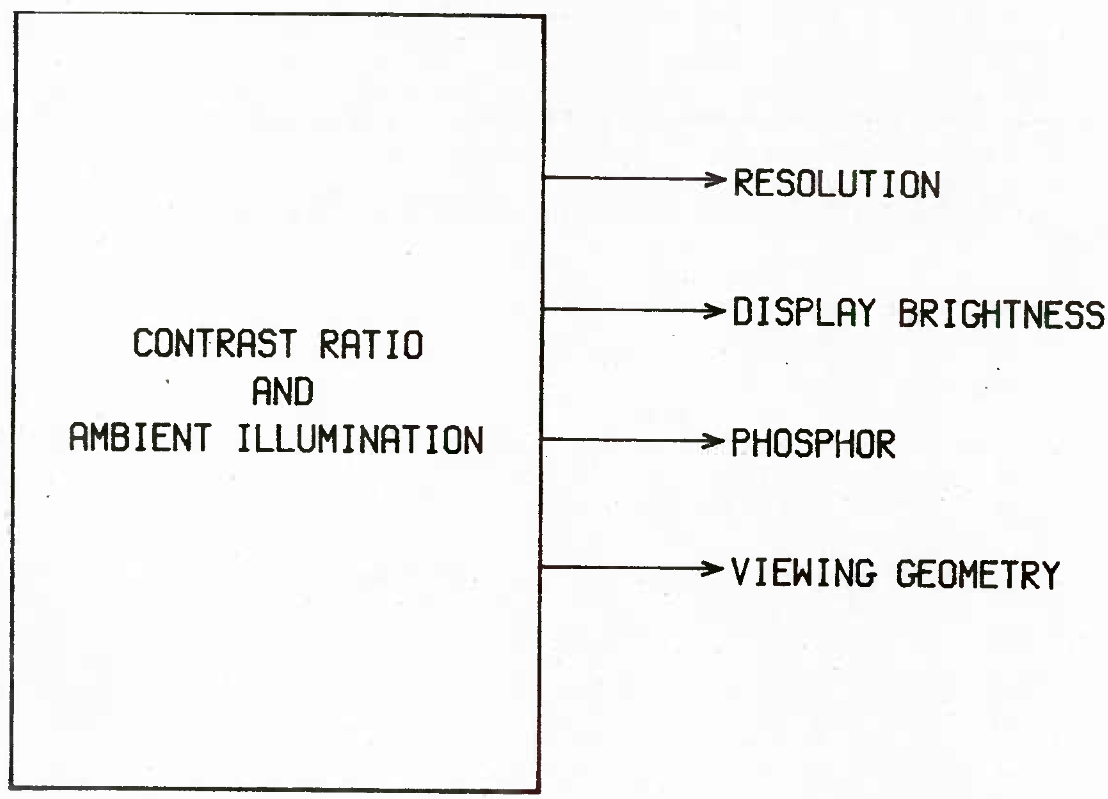


Figure 4. Factors directly affected by contrast ratio and ambient illumination.

The incidence of ambient illumination (either specular or diffused) upon the face of a display very often results in loss of contrast. To compensate for this loss of contrast, the designer must either increase the contrast ratio in the display or control the incidence of ambient illumination either directly or by using attenuating, directional, or polarizing filters.

1.2.1.3 Symbol Characteristics. The legibility of symbols and alphanumeric characters is a function of the following designer controlled factors (see Figure 5):

a. Viewing geometry.
b. Resolution.
c. Registration accuracy.
d. Method of symbol generation.
e. Symbol style.
f. Symbol aspect ratio.
g. Bandwidth.
h. Line spacing.

The symbol characteristics delineated by these factors directly affect the following display characteristics:

a. Resolution.
b. Display brightness.
c. Contrast ratio.
d. Viewing geometry.
e. Write/erase speed.
f. Storage capacity.
g. Line spacing.
h. Registration accuracy.

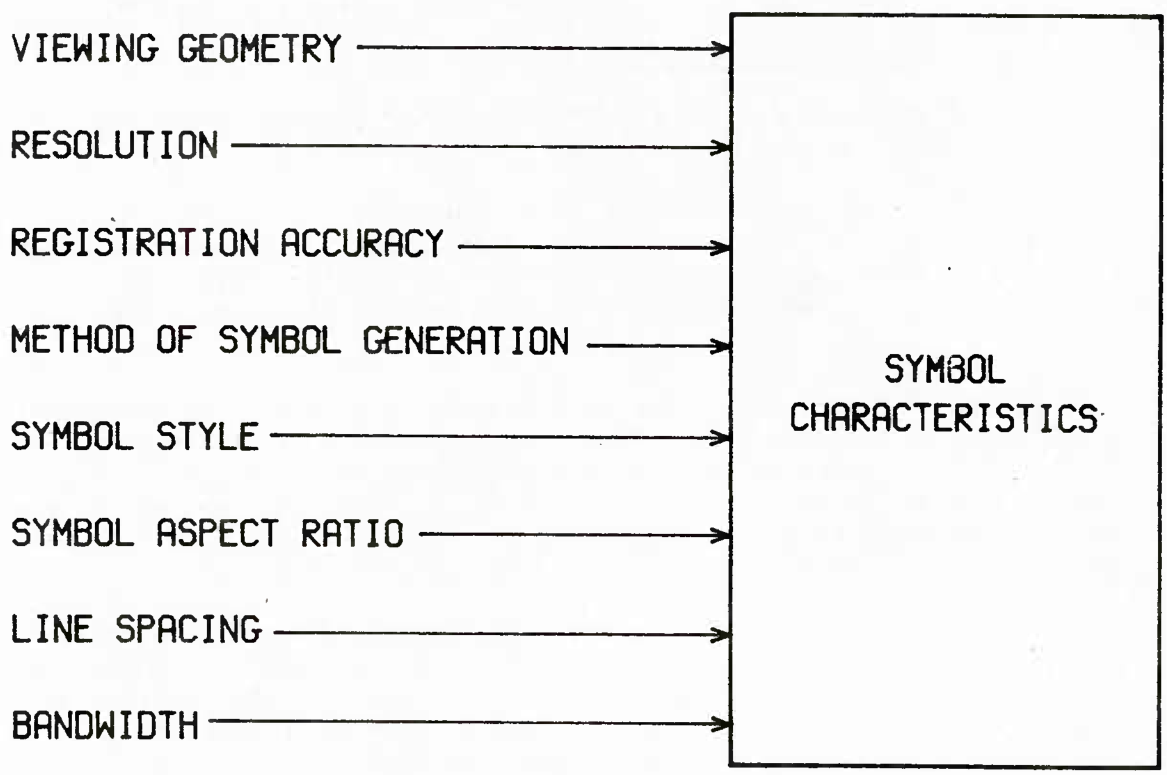


Figure 5. Designer controlled factors affecting legibility of symbols and alphanumeric characters.

As the display characteristics affecting symbol characteristics (see Figure 6) depart from what is defined as optimum, in terms of human performance, two discrete but related effects can be expected.

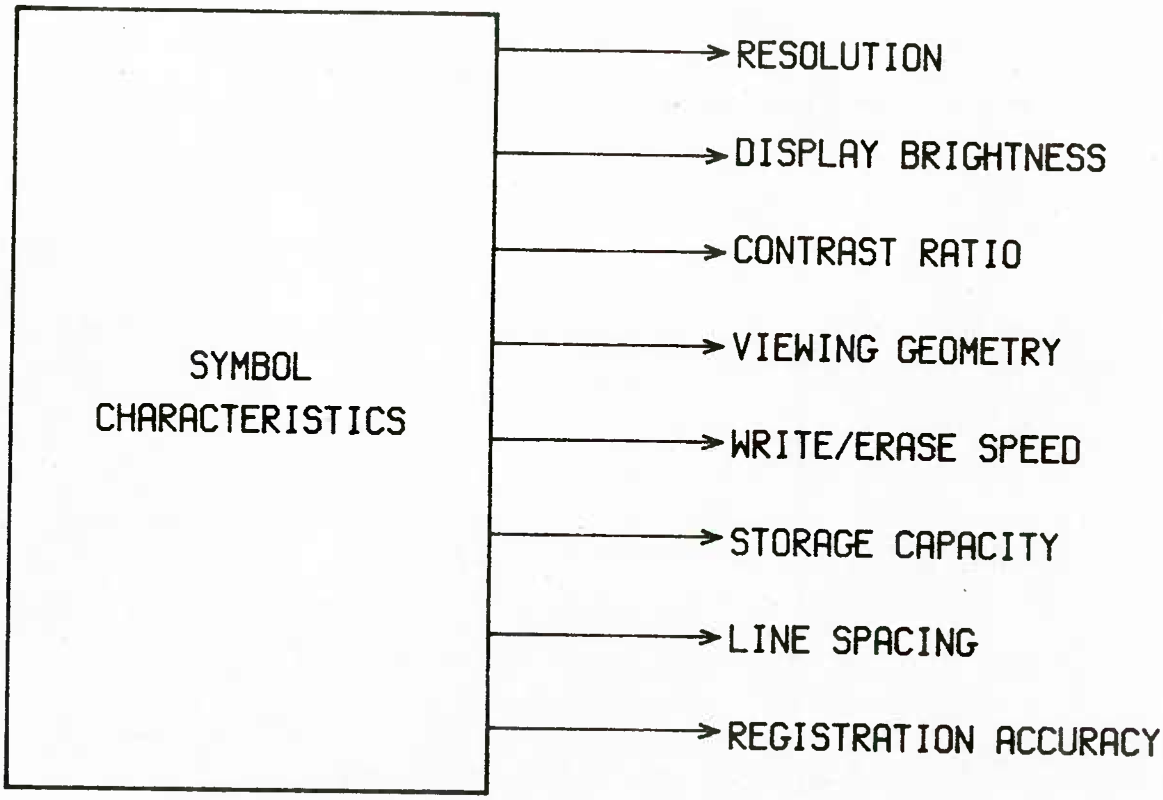


Figure 6. Display characteristics affecting symbol characteristics.

a. Confusion. Confusion is known to occur with certain alphanumeric formats even under optimum display conditions. As the display characteristics listed in Figure 6 are modified to less than optimal in the course of satisfying system design requirements, the confusion ratio, especially with regard to complex groupings of special symbols, will rise.

b. Clutter. One of the major problems presented by today's display systems is simply the overabundance of information being presented at any one time. At an earlier time, the primary problem was to distinguish information or "real" returns from noise (still a problem in some types of systems). Today, the problem is being able to discriminate the required information from the masses of data that have no relevance to the task at hand. This unwanted or unused data is referred to as clutter.

The problem for the display engineer is to determine which data should be displayed to whom and when and, of course, how to implement these determinations. This is a system-dependent and, hence, a human-operator-task dependent problem that can only be solved by specific analysis of information requirements which, in turn, usually requires empirical simulation for exact operational solution.

1.2.1.4 Resolution. Resolution has no simple or agreed-upon definition; rather its definition is a function of the type of display, its method of generation, and, often, the training of the people involved in the design process. Resolution is variously defined by:

a. Size of a focused electron beam spot on the phosphor screen.

b. Seconds of arc, the angular measure of the smallest observable spot in a given pattern.

c. Graininess, the irreducible size of the display medium grain.

d. Lines per unit distance.

For a given display, type the resolution achieved is a function of (see Figure 7):

a. Frame rate.
b. Contrast ratio.
c. Registration.
d. Phosphor.
e. Symbol characteristics.
f. Bandwith.
g. Display brightness.
h. Viewing geometry.

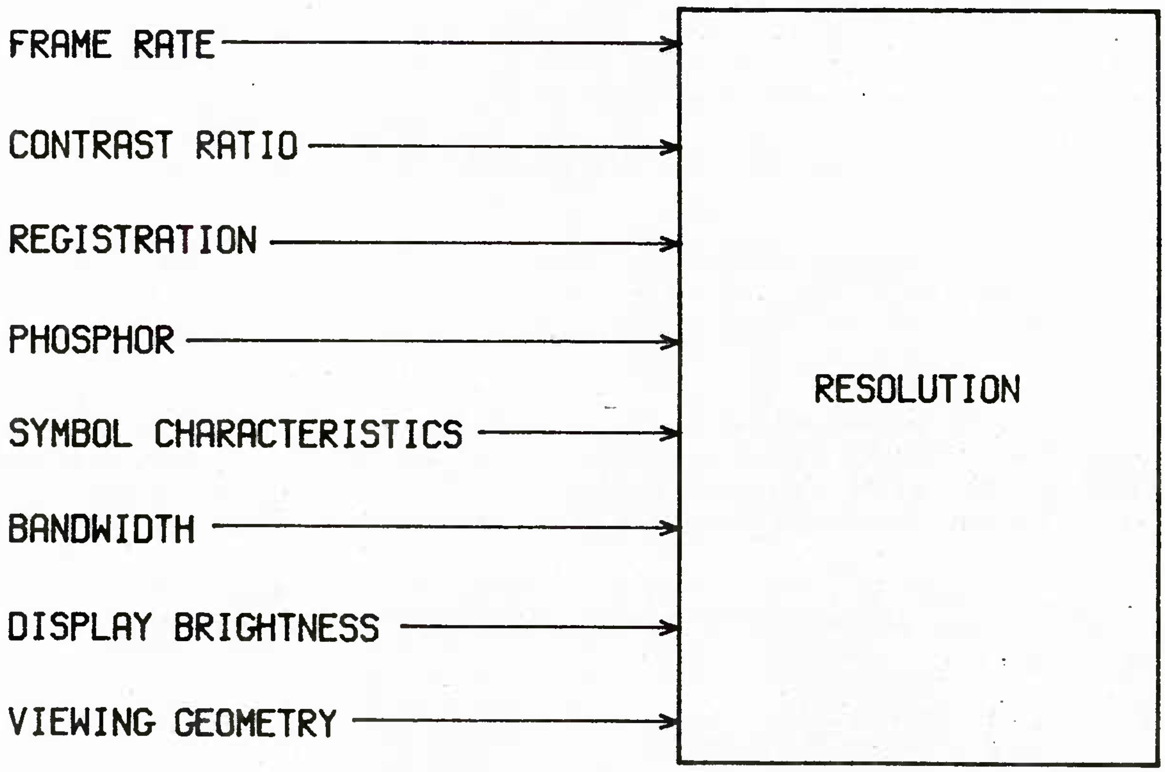


Figure 7. Factors affecting type of resolution achieved.

In turn, the type of resolution achieved directly affects (see Figure 8):

a. Bandwidth.
b. Phosphor.
c. Registration.
d. Symbol characteristics.

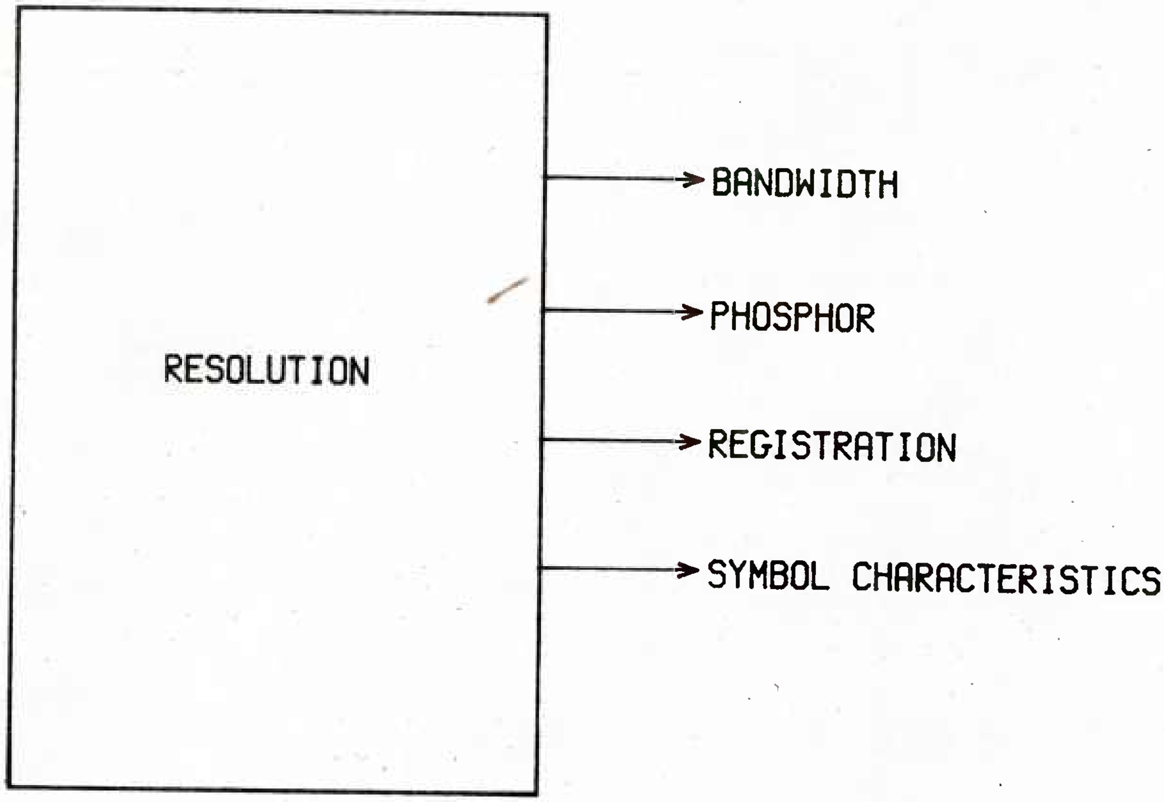


Figure 8. Factors affected by resolution achieved.

Within the limits described above, the resolving capability of the human eye determines minimal resolution levels for the display; optimum human performance is achieved when symbols resolve between 12 to 15 minutes of arc and/or between 10 to 12 lines.

The amount of detail that can be displayed on a CRT display is essentially independent of display size. For example, equal levels of resolution can be achieved in all sizes of CRTs if one is prepared to accept the costs of very high accelerating potentials on the one hand or extreme deflection angles on the other.

1.2.1.5 Bandwidth. Frame rate and resolution influence bandwidth (see Figure 9), which, in turn, influences the following display characteristics (see Figure 10):

a. Resolution.
b. Frame rate.
c. Symbol characteristics.

If one of the constraints imposed upon the display design is a restricted bandwidth, establishing a frame rate within that bandwidth for the efficient, flicker-free display of required information becomes the problem. As the frame rate increases, the number of resolution elements or characters that can be displayed decreases for a given time interval in a given bandwidth.

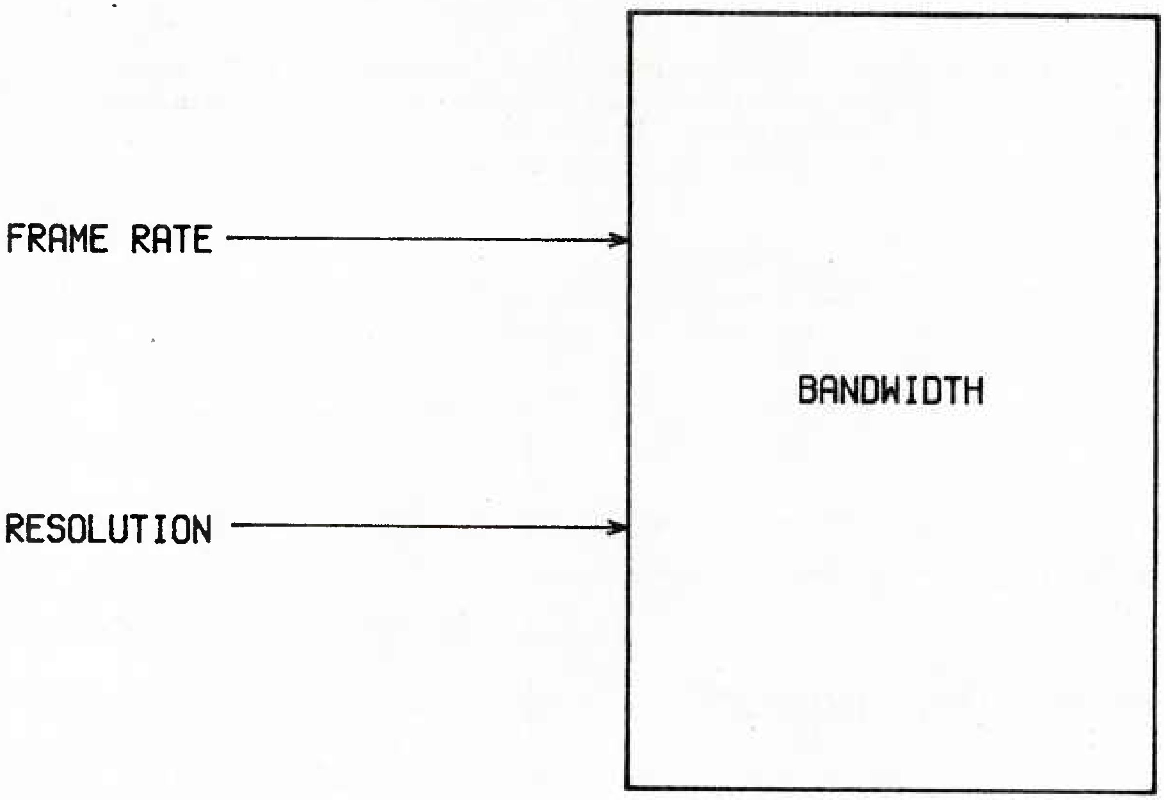


Figure 9. Bandwidth influences.

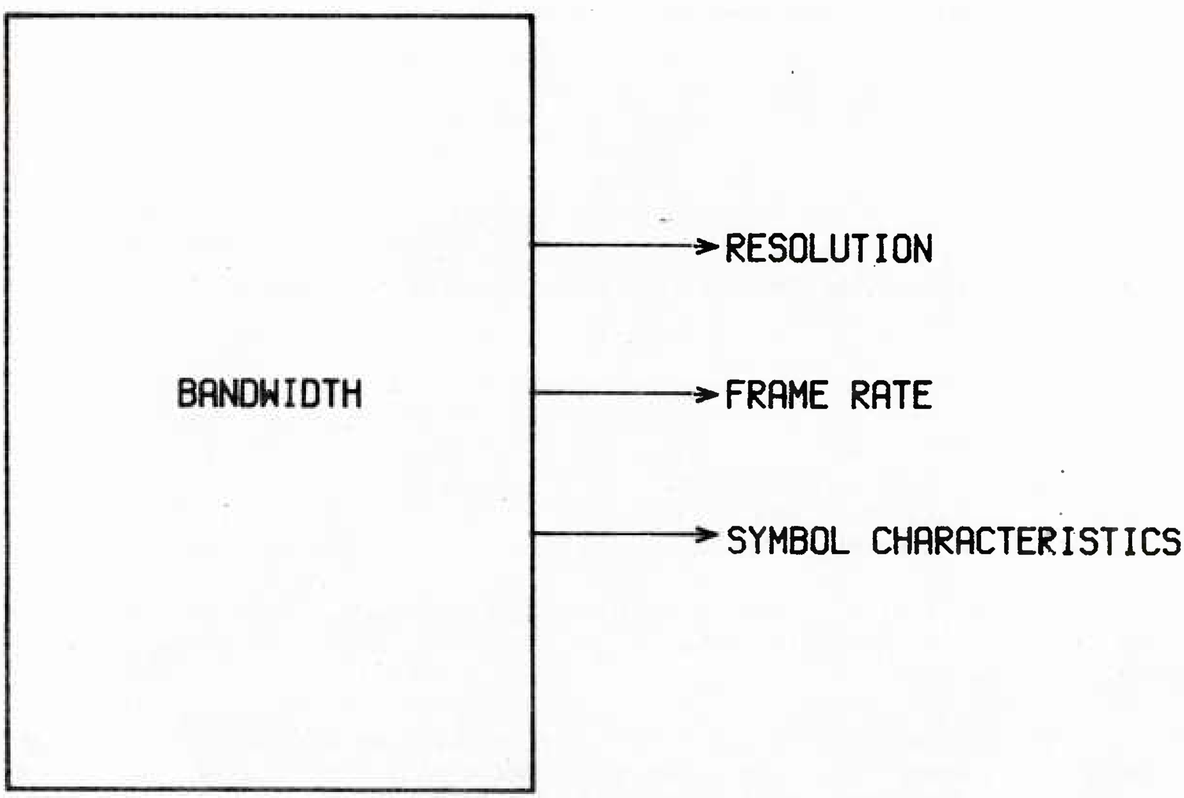


Figure 10. Display characteristics influenced by bandwidth.

1.2.1.6 Registration. As information density and the use of preformatted textual, multicolor, and complex overlaid displays increase, the accuracy with which a target, symbol, or block of information can be positioned on a display becomes more and more important. Registration accuracy is determined by (see Figure 11):

a. Resolution.
b. Symbol characteristics.
c. Display hardware (gun type, deflection technique, etc.).
d. Programming accuracy (in computer driven displays).

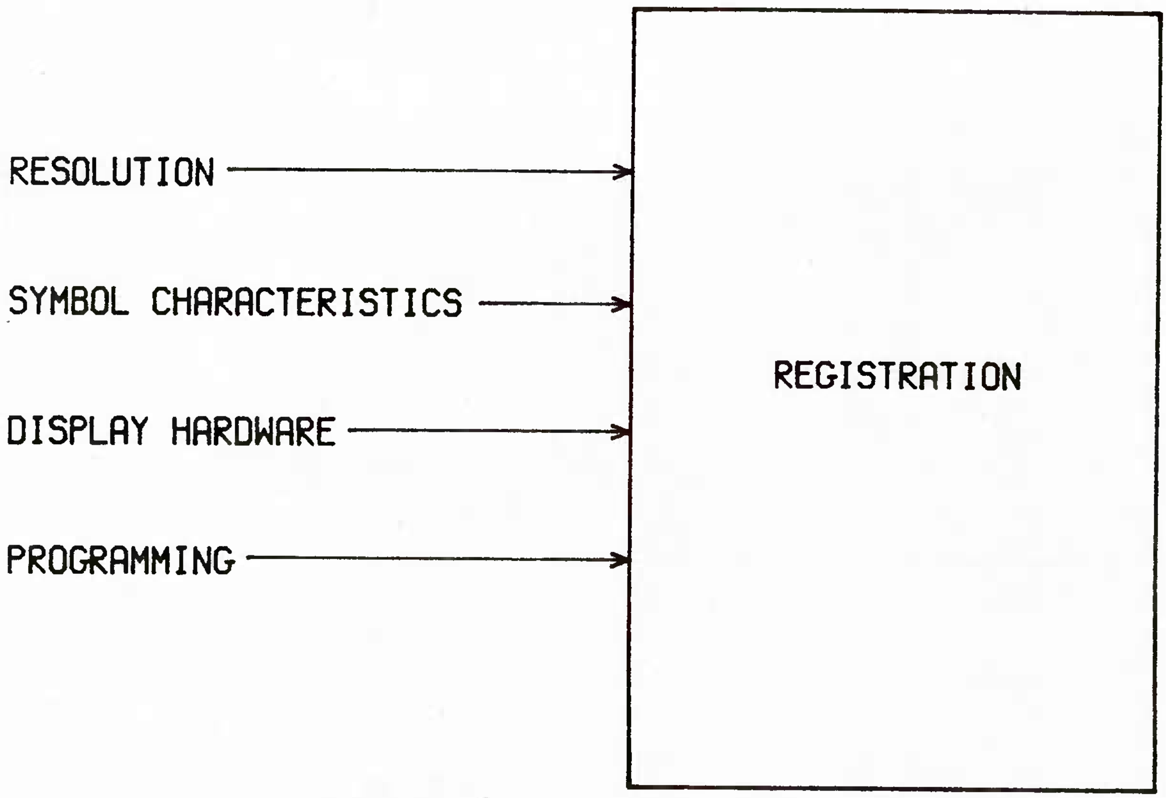


Figure 11. Factors determining accuracy of registration.

Registration accuracy directly impacts on (see Figure 12):

a. Resolution.
b. Symbol characteristics.
c. Display hardware.
d. Programming accuracy.

Registration is extremely critical in color displays. Misregistration can result in the wrong color being displayed, is very annoying to the operator, and degrades operator performance.

While most displays are capable of registration accuracy of .1 percent of screen width, system requirements may not require such a close tolerance; however, to achieve acceptable human performance, 30 percent of stroke width seems to be an acceptable value.

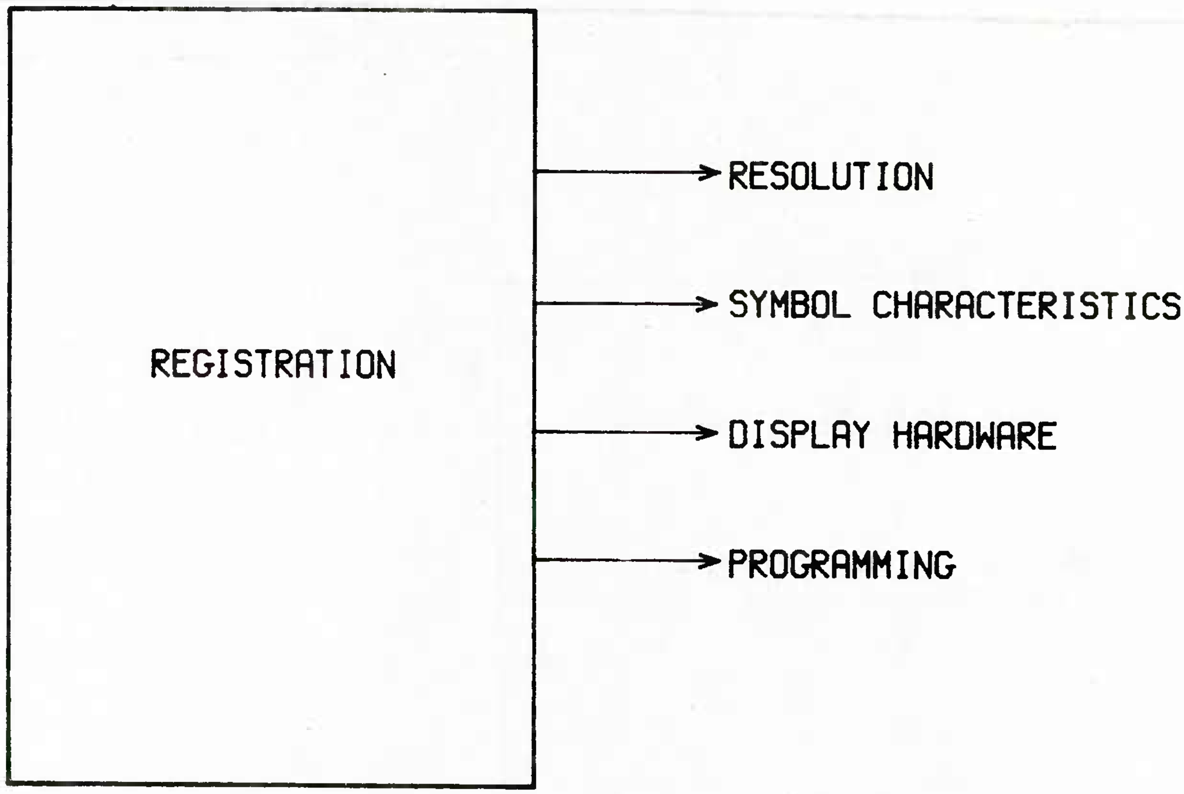


Figure 12. Factors affected by registration.

1.2.1.7 Phosphor Type. The designer of CRT displays is primarily interested in the screen efficiency, decay time, and color of the phosphor. From the human factors viewpoint, the latter two have a direct effect upon human performance.

Decay time, or persistance, is directly related to the CFF of a display and thus is directly related to the required frame rate. The persistance of a display needs to be sufficient for observation, but not enough to cause the appearance of smears and ghosts from previously displayed information. For visual purposes, short-persistance phosphors are used for high repetition rates, slow trace or spot movements; medium-persistance phosphors, for general display applications; long-persistance phosphors, for radar and sonar applications where the picture is refreshed infrequently. Phosphors emitting in the middle of visible spectrum are preferable to those emitting at the blue end of the spectrum, due to human visual capabilities.

Phosphor selection is affected by the following (see Figure 13):

a. Resolution.
b. Display brightness.
c. Ambient illumination.

It directly affects the following factors (see Figure 14):

a. Resolution.
b. Contrast ratio.
c. Frame rate.
d. Write/erase speed.

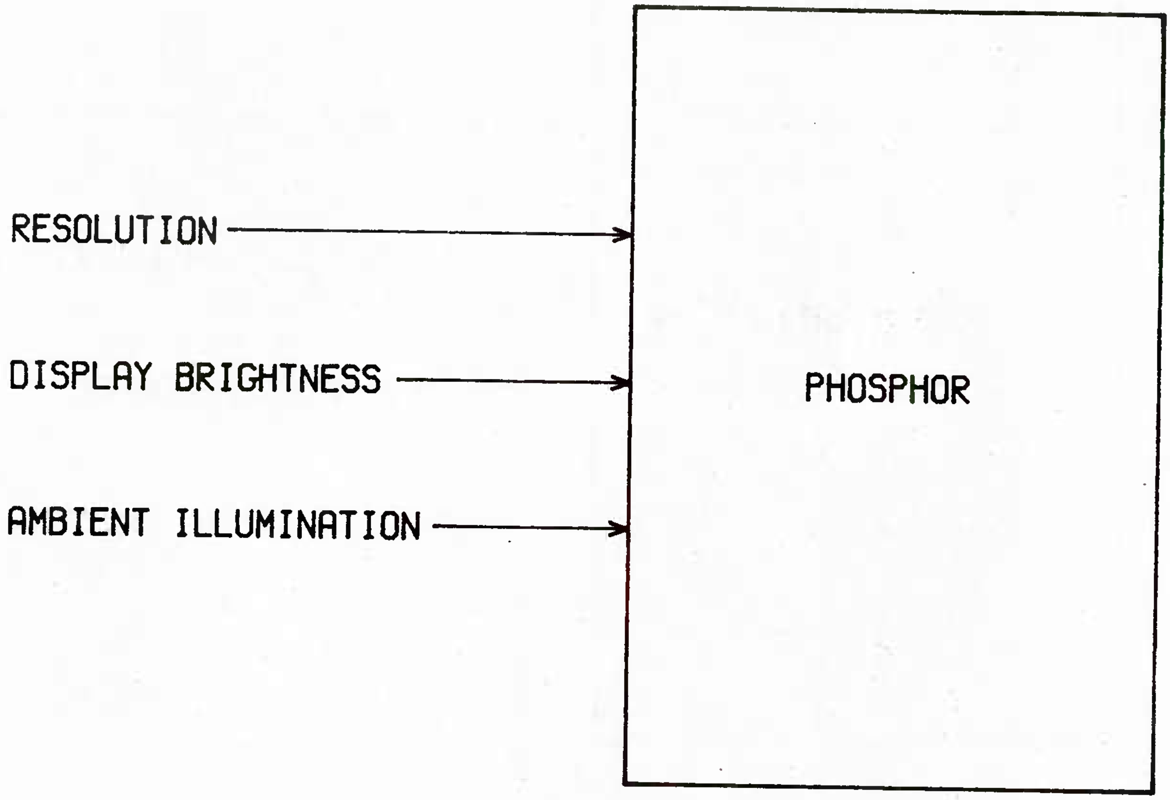


Figure 13. Factors affecting phosphor selection.

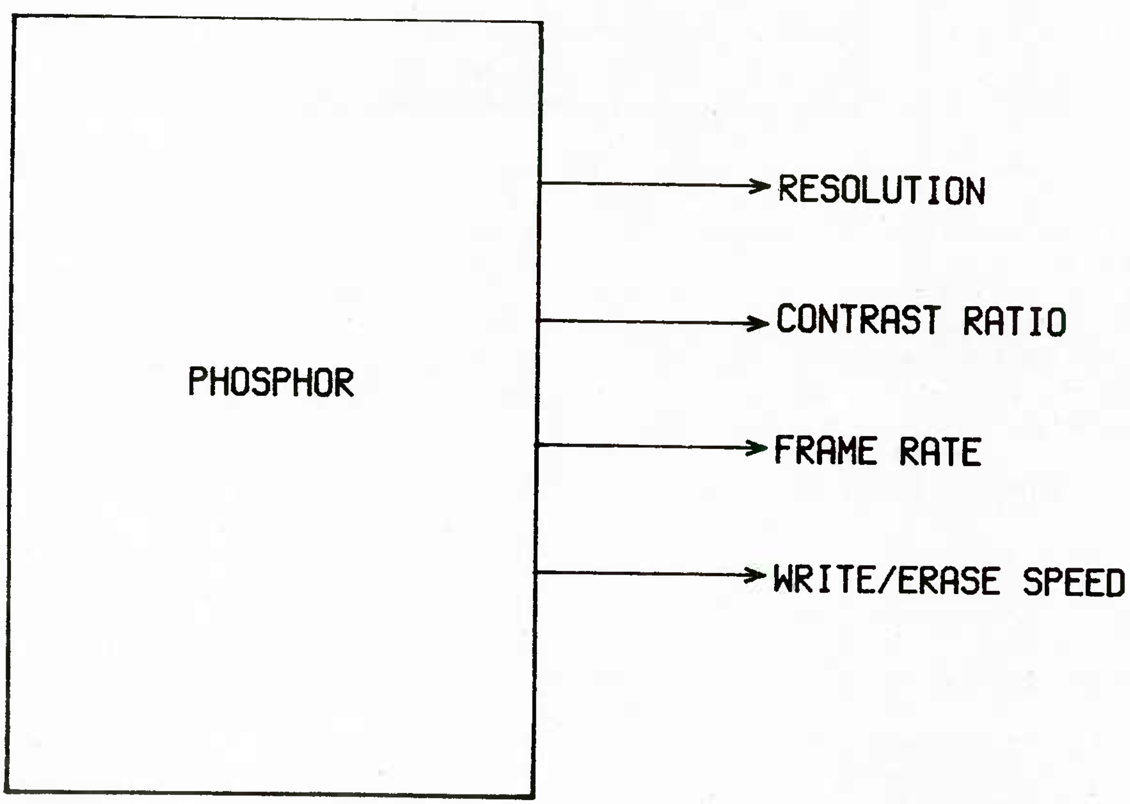


Figure 14. Factors affected by phosphor selection.

1.2.2 Display Design--Group Viewing Case

Almost every command and control system requires that, in addition to displays for the single operator, displays be provided for group viewing. The critical display characteristics that affect human performance in a group viewing situation are identical to those just described for the single viewer, although the specific parameter values may differ.

The most important parameter in the group viewing case, is the effect of viewing angle upon the performance of the group personnel. This is true only when viewing distance is normal for console operators (e.g., 16 to 28 inches).

Viewing angle or viewing geometry is defined as the relationship between the display configuration and the audience space for that display. Viewing geometry for a particular display is a function of (see Figure 15):

a. Room dimensions.
b. Ambient illumination.
c. Symbol characteristics.
d. Audience size.
e. Audience configuration.

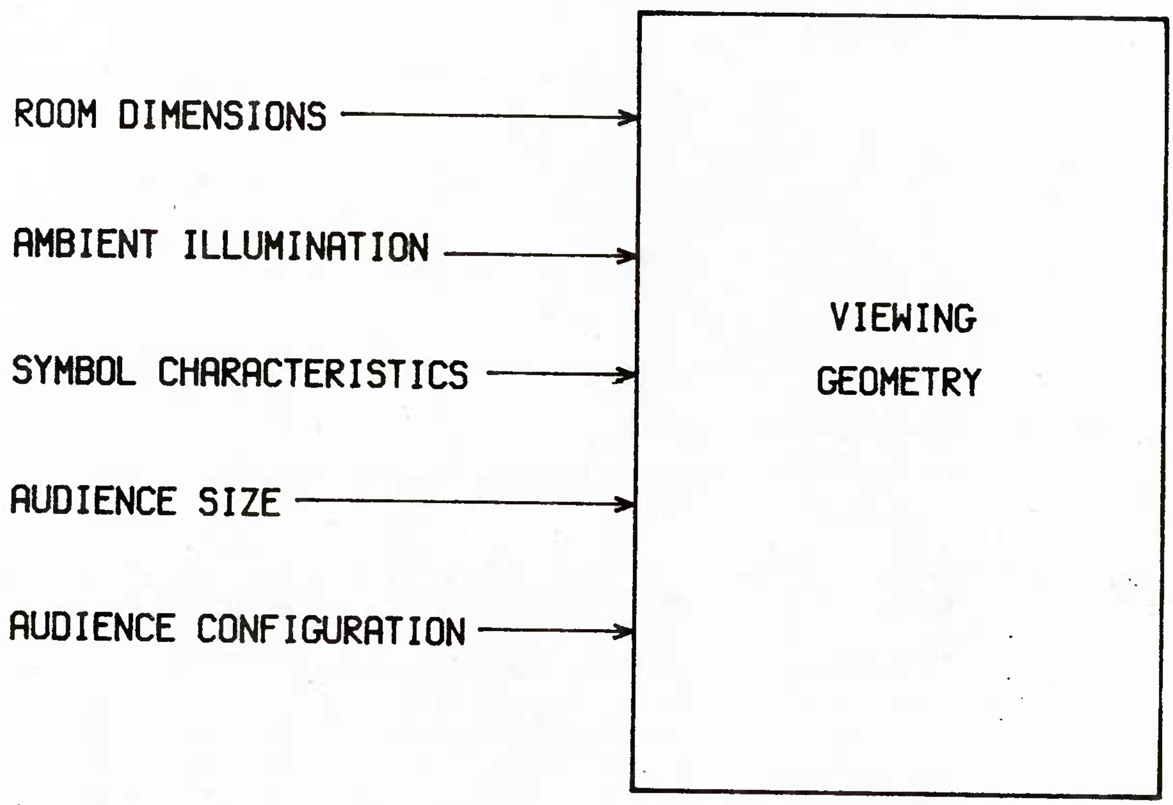


Figure 15. Factors affecting the viewing geometry for a particular display.

Viewing geometry angle directly affects the following (see Figure 16):

a. Room dimensions.
b. Audience size.
c. Audience configuration.
d. Ambient illumination.
e. Display brightness.
f. Resolution.
g. Symbol characteristics.

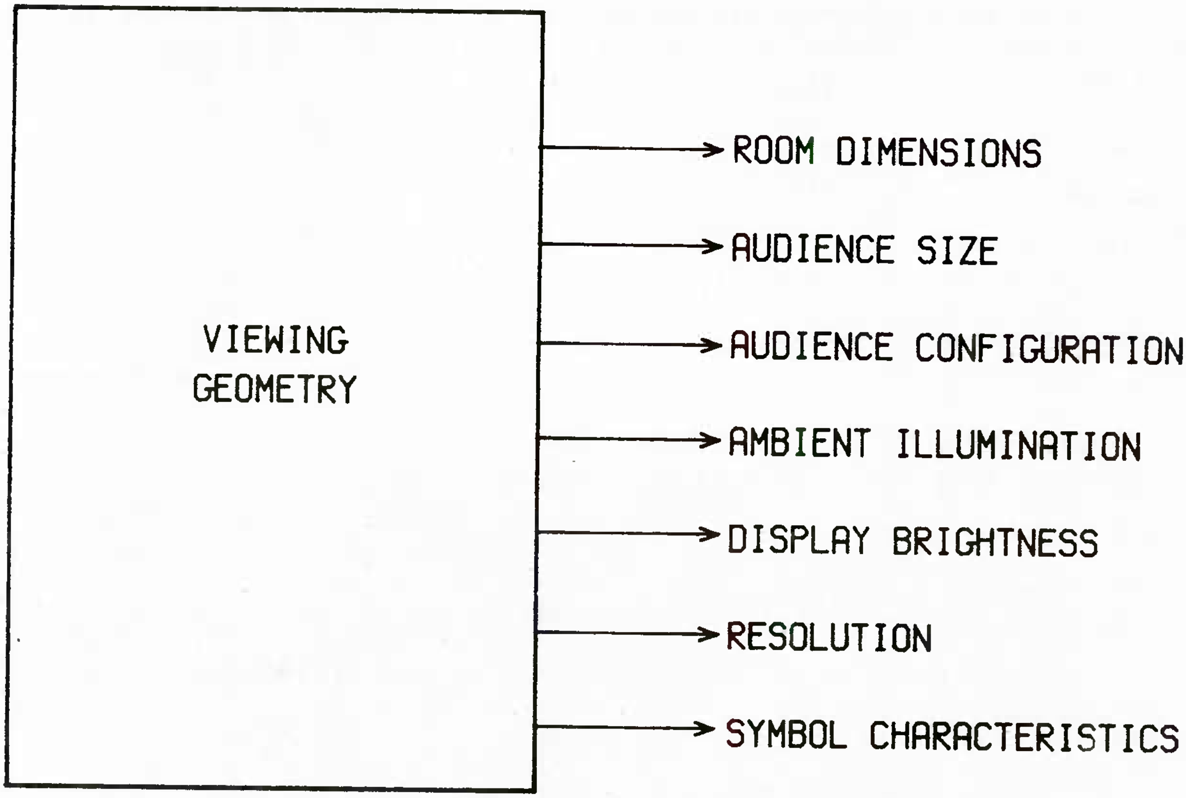


Figure 16. Factors directly affected by viewing geometry.

In considering the question of viewing angle or viewing geometry of a display system designed for group viewing, the designer must address three separate questions.

a. How much information can/should the display convey?
b. How large an audience can/or must it serve?
c. How should the audience and display be arranged for maximum efficiency?

Keep in mind, that while group interaction is limited by small screen size; it is not necessarily increased by increasing screen size. Taking the deterioration of legibility due to both distance and oblique viewing into account, individual symbols must be large enough to be legible from a distance equal to the screen diagonal. This limits the display's capacity and requires the system designer to select an audience configuration that maximizes display utility. It also requires the display designer to structure formats and coding methods, and to select symbols that maximize the utility of the reduced display capacity (Luxenberg & Bonness, 1965).

The characteristics of effective displays and operator/display interactions are illustrated in Tables 1 and 2. The relative importance of display parameters and the availability of knowledge about these parameters are shown in Table 3 (taken from Shurtleff, 1980). Admittedly, there is a certain amount of subjectivity in all these judgments.

Table 1

Characteristics of Effective Displays

1. Individual characters highly legible.
2. Meaningful groups of characters (e.g., words) easily recognizable.
3. Weak signals detectable at all display range scales.
4. Characters readily discernible from each other.
5. Display can be viewed equally well at any required viewing angle.
6. Minimum loss of signal detectability at long and short ranges.
7. Minimum fall-off in screen/scope brightness.
8. Maximum contrast.
9. Minimum image distortion.
10. Fastest possible observer response time, where time is a factor in efficiency.
11. Highest possible observer accuracy in performing visual function.
12. No or very slight flicker.
13. Display can be viewed efficiently in entire operating range of ambient illumination.
14. Minimum equipment delay in responding to user's request for display (as in information-retrieval system).
15. Display parameters (e.g., brightness) adjustable by the user.

Table 2

Operator/Display System Interactions and Influences
(Taken from Humes & Bauerschmidt, 1968)

Operator/Display System Parameters	Image Quality: Image Resolution[a]	Image Quality: Image Luminance[b]	Image Quality: Image Contrast	Image Quality: Image Format Dimensions[c]	Apparent Motion of Image	Image Content[d]	Task Characteristics: Time Available[e]	Task Characteristics: Control Task Difficulty[f]
Display System Parameters								
Frame rate	Moderate	Moderate	---	---	Indirect	---	---	Slight
S/N ratio	Large	Moderate	Moderate	---	---	Moderate	Moderate	---
Display size	Large	---	---	Large	---	---	---	---
Display aspect ratio	---	---	---	Large	Indirect	---	---	---
Display resolution	Large	Large	Large	---	---	Large	---	---
Display gain (brightness)	Moderate	Large	Large	---	---	Large	---	---
Number of shades of grey	Large	Slight	Large	---	---	Large	---	---
Display contrast	Large	Large	Large	---	---	Large	---	---
Scan type (raster composition or orientation)	Slight	Slight	---	---	Slight	Slight	Indirect	---
Phosphor type	Slight	Large	Moderate	---	---	---	Moderate	Slight
Phosphor persistance	Indirect	---	---	---	Slight	---	---	---
Workplace/Job/Operator Parameters								
Task loading	---	---	Large	---	---	---	Large	Large
Operator training and experience	---	---	---	---	---	---	Large	Large
Visual abilities	Moderate	---	---	---	Large	Slight	---	Slight
Display viewing distance	Moderate	---	---	Large	Moderate	Moderate	Moderate	Large
Viewing time	---	---	---	Moderate	Large	---	Large	Large

Legend:

Slight = Weak interrelationship.
Moderate = Significant interrelationship (second order effects).
Large = Very sensitive interrelationship (first order effects).
Indirect = Relationship not linear; other variables involved.

[a]Image resolution includes noise, sharpness, definition, etc. across the entire image.

[b]Image luminance includes image highlight brightness, maximum and minimum useful luminance levels, grey level luminances, etc.

[c]Image format dimensions include size, shape, aspect ratio, etc.

[d]Image content includes all other image parameters relevant to TV viewing that describe and/or bear information about the overall and detail characteristics of the displayed image.

[e]Time available refers to the duration during which an image is available or within which a task must be completed.

[f]Control task difficulty includes the response complexity, required response accuracy, type, frequency, and magnitude of items that must be nulled or tracked, type, frequency, and magnitude of outside distractions, etc.

Table 3

Physical Parameters of Symbol Displays
(Adapted from Shurtleff, 1980)

Display Parameters	Importance		Availability of Technical Knowledge		
	Major	Secondary	Good	Fair	Poor
Classical					
Light Factors					
Wavelength	X	-	-	X	-
Luminance	X	-	-	X	-
Luminance contrast	X	-	-	X	-
Direction of contrast	-	X	-	X	-
Luminance variations	-	X	-	-	X
Color contrast	-	X	-	X	-
Symbol Factors					
Height	X	-	X	-	-
Width	X	-	X	-	-
Stroke width	X	-	X	-	-
Height-to-width ratio	X	-	X	-	-
Font	X	-	X	-	-
Horizontal spacing	X	-	X	-	-
Vertical spacing	X	-	-	-	X
Display Surface Factors					
Size of usable area	-	X	-	-	X
Height-to-width aspect ratio	-	X	-	X	-
Glare	-	X	-	X	-
Modern					
Optical Factors					
Defocussing	X	-	X	-	-
Temporal Factors					
Refresh Rate	-	X	-	X	-
Electronic Factors					
Long-term instability (drift)	-	X	-	-	X
Short-term instability (jitter)	-	X	-	-	X
Linearity	-	X	-	-	X
Positioning accuracy	-	X	-	-	X
Symbol Generation Factors					
TV raster-scan					
Vertical resolution	X	-	X	-	-
Video bandwidth	X	-	X	-	-
Direction of scan	-	X	-	X	-
Direction of contrast	-	X	-	X	-
Dot matrix					
Number of dots in matrix	X	-	X	-	-
Dot element shape	-	X	-	X	-
Dot separation	-	X	-	X	-
Missing, distorted, or misplaced dots	-	X	-	-	X
Stroke Matrix					
Generation technique	X	-	-	X	-
Stroke-matrix size	X	-	-	X	-
Writing speed	-	X	-	-	X
Positioning accuracy	-	X	-	-	X

SECTION 2

VISUAL DISPLAY PARAMETERS

2.0 VISUAL DISPLAY PARAMETERS

2.1 Definitions

a. Bandwidth. The difference between the limiting frequencies of a continuous frequency band. Specifying the bandwidth, which is basic to any display system, describes the available resolving power of the system. Resolving power refers to the vertical, horizontal, and time (frame rate) resolution capabilities of the system and also involves grey levels.

Commercial television bandwith is approximately 4 MHz with certain high resolution TV systems achieving 25 MHz (Humes & Bauerschmidt, 1968).

b. Brightness. (Photometrically defined as luminance.) The amount of light emitted from the display surface. Also, the luminous intensity of any object as viewed by an observer. Brightness is commonly expressed in foot-Lamberts (fL) or candles per square meter (cd/m^2). Brightness is highly subjective and depends on object size, viewing angle, wavelength of the light, background light level, and adaption of the eye. The brightness ratio between the display viewed and the surrounding area should be close to 2:1 for best viewing conditions. Figure 17 indicates the minimum visual angle that an observer can resolve at various background brightness levels--the greater the brightness the ratio, the smaller the object that can be recognized.

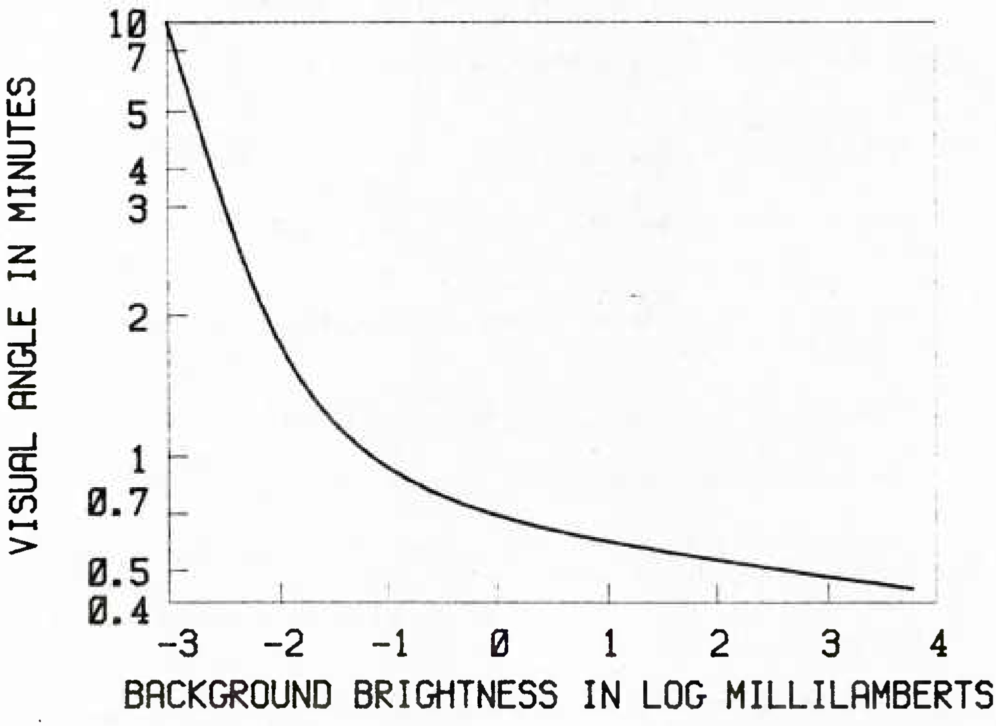


Figure 17. Minimum visual angle resolved at various brightness levels (Moon & Spencer, 1944).

Brightness levels for most complex displays under normal ambient illumination vary from 20 to 70 fL. Symbol brightness on CRT displays is about 46 fL. Any luminance above approximately 25 fL is probably adequate, assuming adequate contrast. For values below this, it is difficult and expensive to reduce background luminance sufficiently to maintain adequate contrast. Brightness of displays used in dark adapted areas (radar, sonar, CIC, etc.) should be below 2.0 fL.

The sources reviewed by Banks, Gertman, and Petersen (1982) made a number of recommendations for brightness, but, before reviewing them, it is desirable to identify these sources and list the acronyms with which they will be referred to herein:

(1) The Technical University of Berlin--TUB (Cakir, Reuter, von Schmude, & Armbruster, 1978).

(2) Defense and Civil Institute of Envrionmental Medicine, Toronto, Canada--DCIEM (Gorrel, 1978).

(3) DIN (German Standards Organization, Draft DIN Standard 66234, no author, no date).

(4) Inca-Fiej Research Association, Federal Republic of Germany--VDT (Cakir, Hart, & Stewart, 1979).

(5) MIL-STD 1472C--MIL-STD (Department of Defense, 1981).

(6) International Business Machines Corporation--IBM (Engel & Granda, 1975).

(7) British Royal Navy--BRN (1971).

(8) EG&G Idaho, Idaho Falls, Idaho--EG&G (Banks, Gertman, & Petersen, 1982).

(9) Swedish National Board of Occupational Safety and Health--SNBOSH (Directive 136, January 1, 1979).

(10) University of London--U of L (Reading, 1978).

The following recommendations were made with regard to brightness:

(1) EG&G--65 cd per m^2 minimum under sufficient contrast conditions.
(2) DCIEM--25 fL (85 cd per m^2) minimum.
(3) VDT--45 cd per m^2 minimum; 80 to 160 cd per m^2 preferred.
(4) BRN--80 to 160 cd per m^2.

Snyder and Maddox (1978) conclude that any display luminance above 65 cd per m^2 is adequate as long as sufficient contrast is maintained. This value is reasonable for terminals used in a typical office environment.

c. Aspect ratio, symbol. The ratio of display-symbol width to height. An optimum value is difficult to pinpoint. On nonelectronic displays, a ratio of 3:4 produces greatest legibility. Values from 1:2 to 1:1 are acceptable (Buckler, 1977). This is not a significant parameter.

c. Aspect ratio, display. The ratio of rectangular display screen width to height. Common values are:

(1) TV commercial--4:3 (1.333).
(2) Motion picture, 16 mm--1.338.
(3) Motion picture (standard screen), 35 mm--1.373.

d. Chromaticity. The color quality of light as defined by chromaticity coordinates of the Commission Internationale de l'Eclairage (CIE) color coordinate system (see Figures 18 and 19). It accounts for dominant wavelength and purity only. Chromaticity is specified by the location on the X and Y axes of a sample color on the spectrum locus. The spectrum locus represents the chromaticities of spectrally pure stimuli. Purity is determined by the location of the sample color in relation to a reference white. Color recommendations for CRT displays are as follows:

(1) EG&G--User's choice as long as there is no interaction between screen hue and the hue or shades of symbol colors.

(2) TUB--Yellow-green most suitable; symbol and background colors should be similar.

(3) DIN--Green through orange.

(4) DCIEM--Green or white only.

(5) VDT--Personal preference.

As can be seen, the recommendations are either user's choice or green/white, which suggests that user's choice is most reasonable.

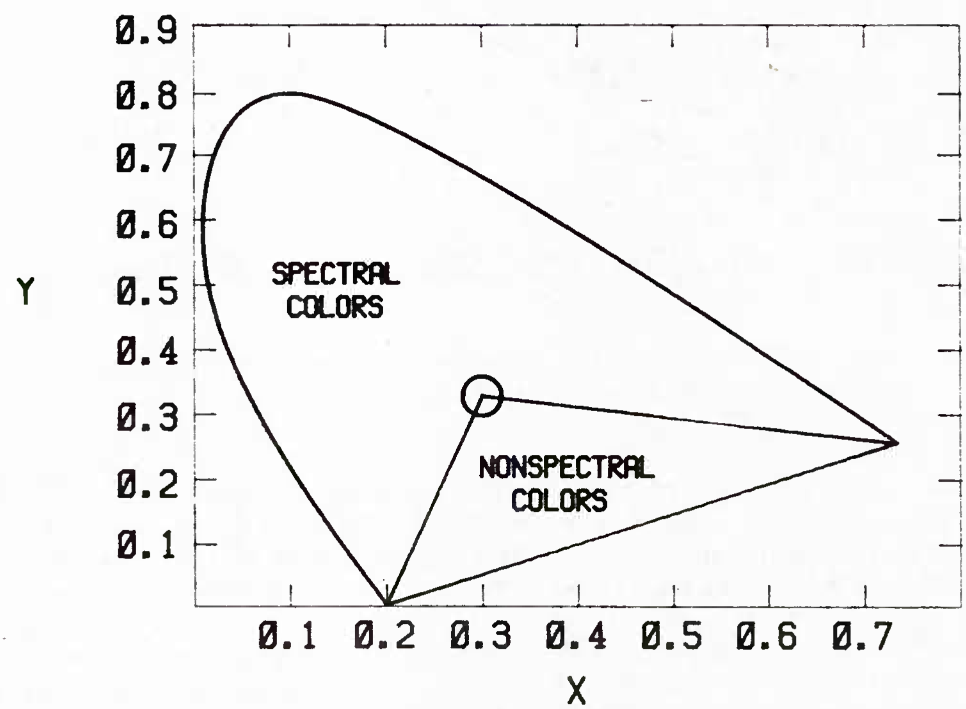


Figure 18. Division of real chromaticities into spectral and nonspectral parts (Kelly, 1965).

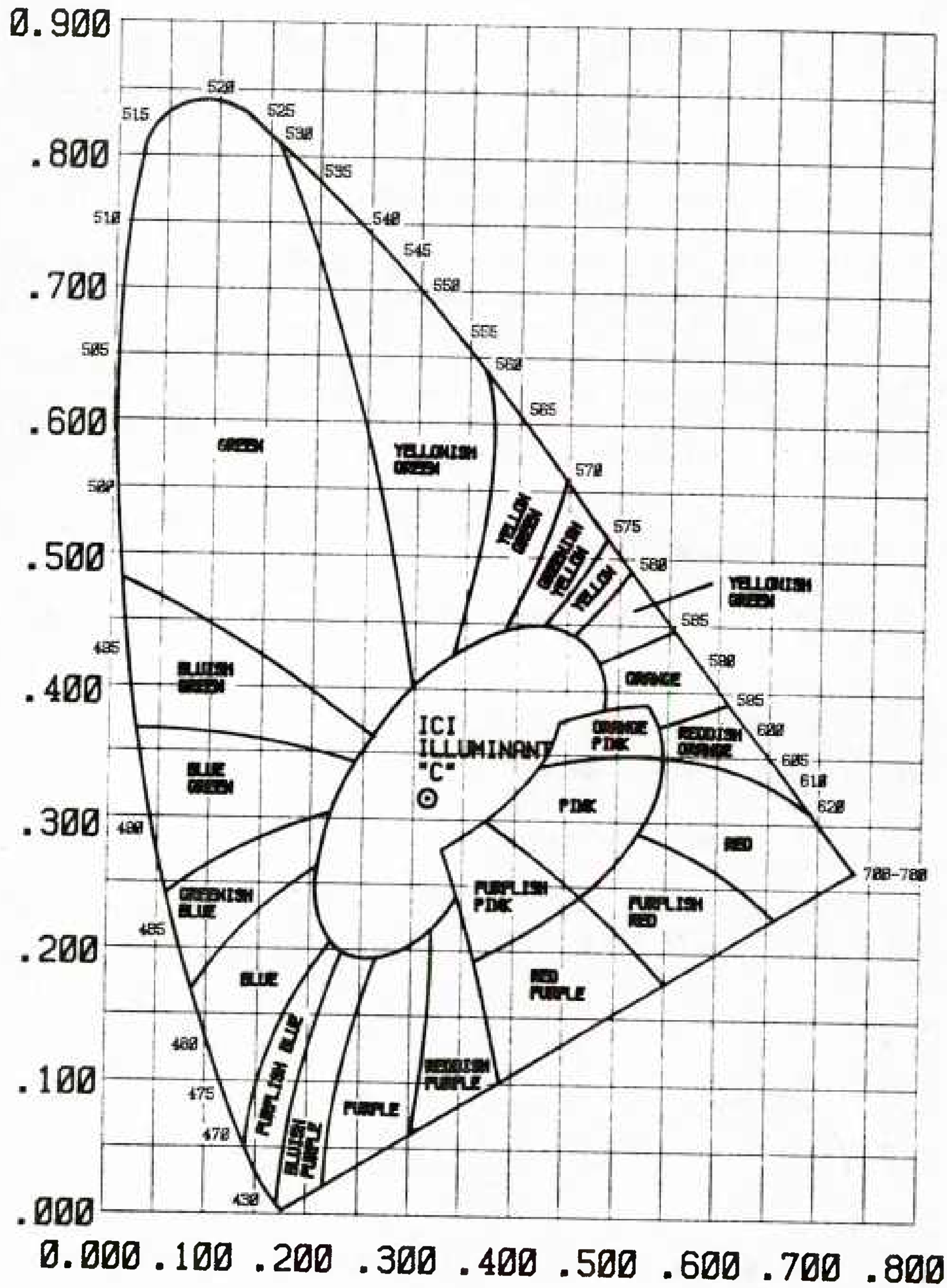


Figure 19. The (x,y)-chromaticity diagram of the international commission on illumination system.

Note. The abscissa, x, is the ratio of the tristimulus value, X, to the sum of all three (X+Y+Z). The ordinate, y, is the ratio of Y to this sum. The parts of the spectrum locus are identified by wavelength in millimicrons. The region bounded by this locus and the straight line (purple border) joining its extremes represents all chromaticities producible by actual stimuli. The division of this chromaticity diagram into a number of regions corresponding to various hues surrounding a central region to which no hue name is given is from Kelly's work on color designations for lights. It refers to observation of self-luminous areas against a dark background (Judd, 1950).

f. Contrast, percent of. Ratio of object brightness (B_o) to background brightness (B_b). Percent of contrast (C) may be defined as:

$$\% C = \frac{B_o - B_b}{B_b} \times 100. \tag{2.1}$$

In this equation, the object is brighter than the background. Contrast can vary from 100 to 0 percent for objects darker than their background and from 0 to infinity for objects brighter than their background. Where the background is brighter (B_{max}) than the object (B_{min}), the following equation may be used:

$$\% C = \frac{B_{max} - B_{min}}{B_{min}} \times 100. \tag{2.2}$$

g. Contrast efficiency. Still another way of expressing contrast is by the ratio of the luminance difference to luminance sum:

$$C = \frac{B_{max} - B_{min}}{B_{max} + B_{min}} . \tag{2.3}$$

This quantity is sometimes called modulation (see paragraph 2.1.bb), modulation contrast, and visibility ratio.

Self (personal communication) considers it better to use

$$C = \frac{B_{max} - B_{min}}{B_{max}} \tag{2.4}$$

for targets either lighter or darker than their background (then varies from 0 to 100 percent for either).

h. Contrast ratio. Contrast ratio (CR) is expressed as the ratio of maximum luminance to minimum luminance:

$$CR = \frac{B_{max} - B_{min}}{B_{min}} . \tag{2.5}$$

Figure 20 shows contrast thresholds for various brightness levels and object sizes for 99 percent probability of detection. Figure 21 shows minimum visual angles for various contrast ratios. Both Figure 20 and Figure 21 should be used with caution, since they reflect laboratory situations only.

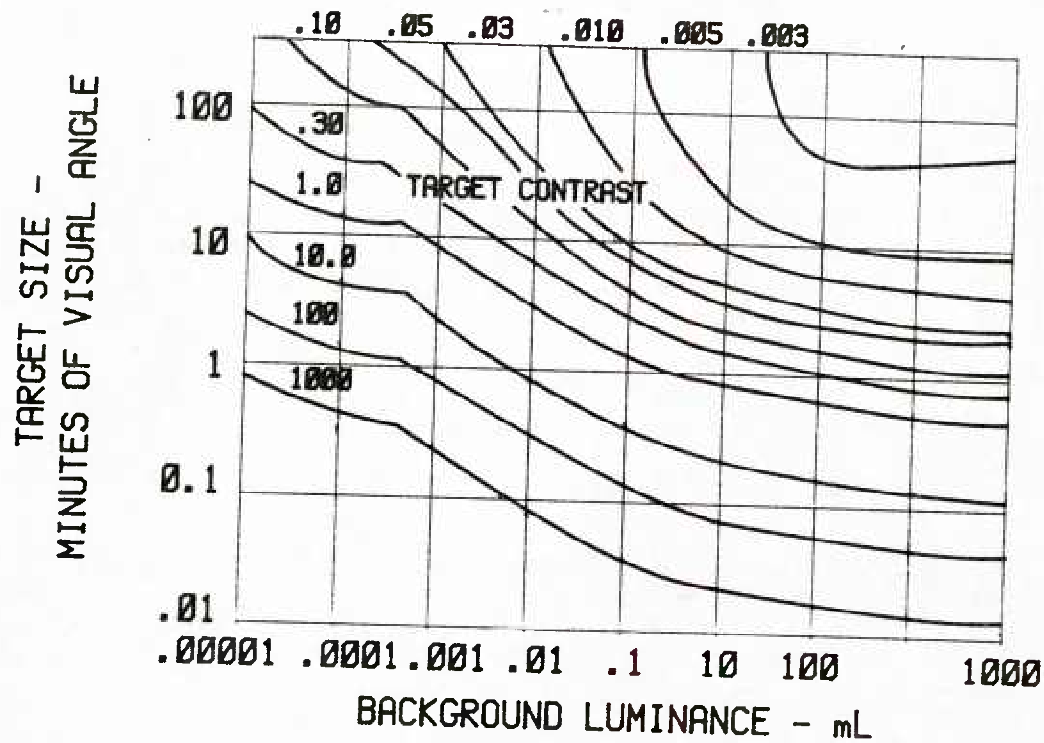


Figure 20. Relation between target size, threshold background luminance, and contrast (Lovelace Foundation, 1968).

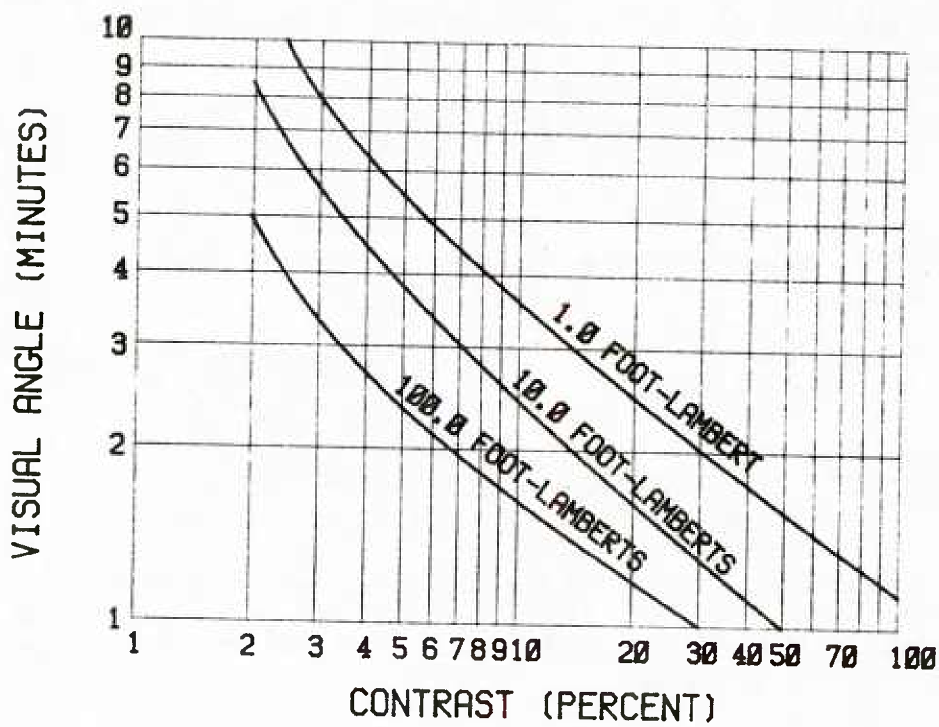


Figure 21. Minimum visual angles for various contrast ratios at three levels of background illumination (Cobb & Moss, 1928).

Another factor related to contrast is the ratio of display luminance to surround luminance. Buckler (1977) recommends a display-surround contrast of no more than 2:1. The definition of the contrast ratio for CRT displays is a special case where the writing is usually brighter than the background, and the frequently used form to express this type of contrast is

$$C_t = \frac{B_s - B_w}{B_s}, \tag{2.6}$$

where B_s is the brightness of the screen from ambient light and B_w is the brightness of the written line when ambient light is excluded (Bryden, 1969).

A minimum contrast ratio of 3:1 to 4:1 is a rather common recommendation. However, a number of authorities provide varying standards:

(1) TUB--5:1 to 10:1 with a background of at least 20 cd per m^2.

(2) DIN--3:1 minimum, 6:1 to 10:1 preferred, 15:1 maximum.

(3) DCIEM--4:1 minimum in an ambient of 75 to 100 fc.

(4) VDT--3:1 minimum, 8:1 to 10:1 optimum with a background luminance of between 15 and 20 cd per m^2.

(5) MILSTD--10:1 minimum using white on black background.

(6) IBM--0.875 modulation contrast.

(7) EG&G--Variable from 4:1 to 7:1 depending upon ambient lighting and user preference.

(8) Buckler (1977) gives a range of 8.5:1 to 10:1.

CRT symbols tend to be relatively blurred due to the relatively gradual (rather than sharp) symbol-background luminance gradients. Contrast enhancing devices all too often enhance contrast at the expense of a reduction in luminance (and frequently with additional symbol blurring).

i. Dynamic visual acuity. Most of the measures of visual acuity are for static conditions. In some display situations, the observer will be called upon tc detect, recognize, or identify moving targets. Dynamic visual acuity is generally defined in terms of the smallest detail that can be detected when the target is moving. At speeds above 20 degrees per second, angular movement of the target decreases the threshold of visual acuity.

Dynamic visual acuity as a function of age is shown in Figure 22 for minimum separable acuity and target motion--through 180 degrees. The loss of acuity increases rapidly as the rate of motion exceeds 60 degrees per second (Grether & Baker, 1972).

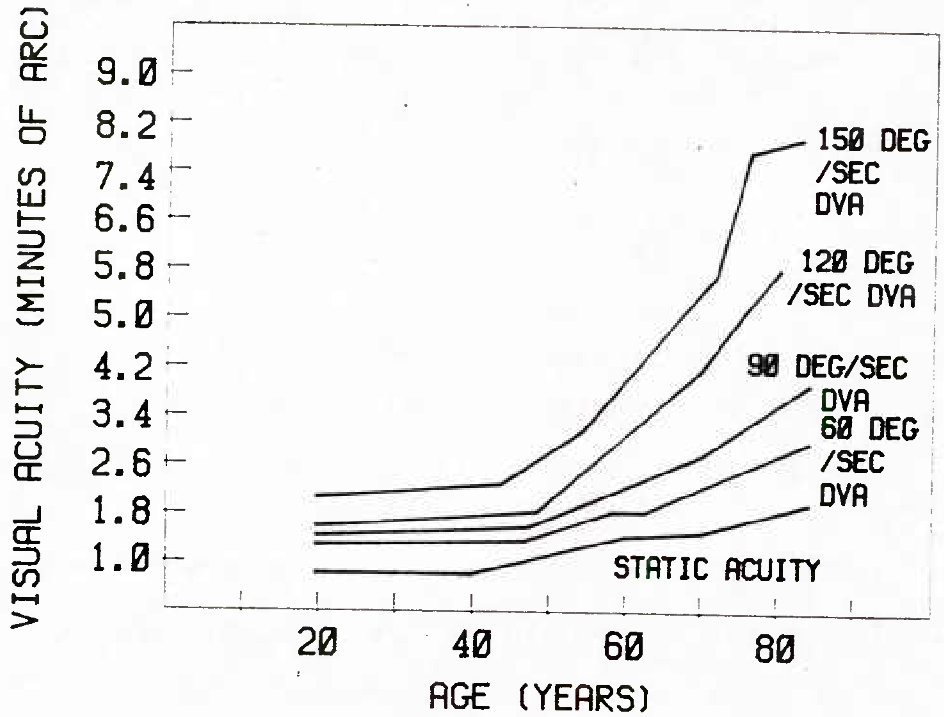


Figure 22. The variation of static and dynamic visual acuity (DVA) with age (after Burg, 1966).

j. Flicker. A fluttering (flashing) sensation caused by picture brightness alterations. Flicker is no longer perceptible above a critical flicker frequency (CFF), usually considered to be 30 to 55 Hz. The primary determinants of flicker for a specific display are the following:

(1) Frame rate.
(2) Brightness.
(3) Ambient illumination.
(4) Phosphor used.
(5) Visual angle (subtended by the display).
(6) Amplitude and waveform of the variation.
(7) Location of the stimulus on the retina.

Figure 23 shows the relationship between CFF, display brightness, and frame rate for certain common phosphors (Bryden, 1969).

In general, a 60 Hz regeneration rate, which is the rate of home television receivers, is sufficient to prevent the preception of disturbing flicker. The aim is to establish the lowest possible regeneration rate for a given set of display conditions in order to minimize the bandwidth necessary to carry the information to the display. An increase in regeneration rate means a decrease in the number of picture elements or characters that can be displayed at one time for a given bandwidth. Individual observer differences limit the accuracy of prediction of minimum required regeneration rate to from ± 10 to ± 25 percent.

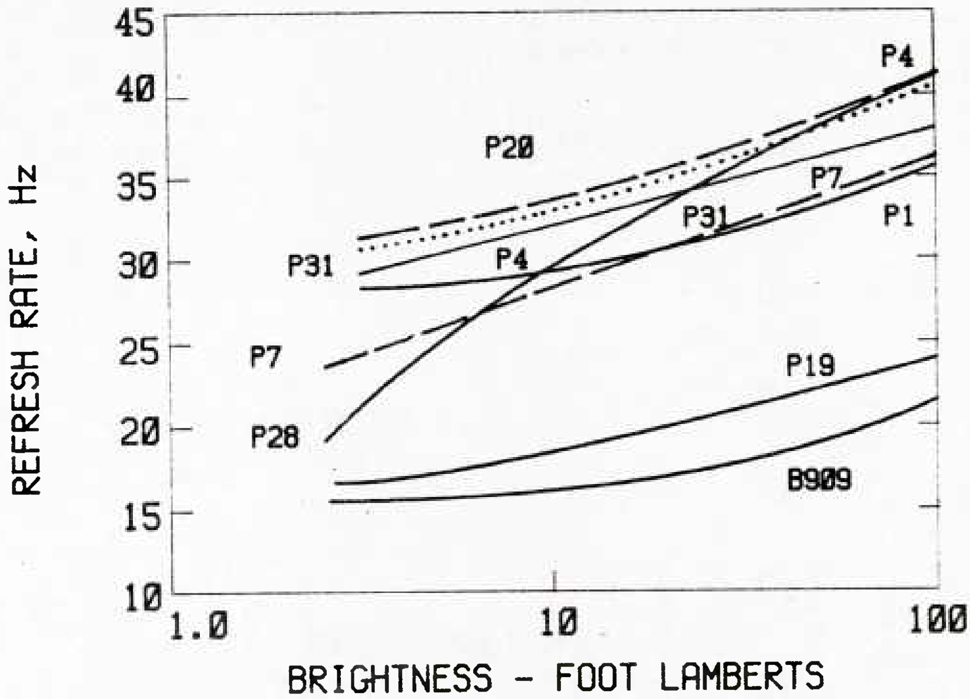


Figure 23. Lowest frame rate that will give freedom from flicker for 90 percent of observers.

CFF is proportional to the logarithm of both angular size and luminance. Voltage variations within a system can result in as much as 15 Hz variation in the regeneration rate required to prevent display flicker.

In practice, phosphor and ambient illumination are the main determinants of required frame rate. Long persistence phosphors have relatively low brightness modulation and, hence, relatively low frame rates will be required to prevent flicker. These percentages can be calculated from the JEDEC (1966) persistence curves for any phosphor and any regeneration period. In Table 15, several phosphors are ranked in terms of their persistence for frame rates of 1/30 and 1/60 second. Figure 24 illustrates the effect of various levels of ambient illumination on CFF.

k. Fluorescence. Luminescence having a persistence shorter than 10^{-8} second. This is the initial output from a phosphor when activated.

l. Foot-candle (fc). A unit of illumination, equal to the amount of light falling on an area of 1 square foot that has received a uniform light flux of 1 lumen.

m. Foot-Lambert (fL). A unit of brightness equal to the brightness of a perfectly diffusing and reflecting surface illumination by 1 foot-candle.

n. Frame rate. Speed in Hz with which a displayed image is updated (alternatively referred to as regeneration rate, update time, refresh rate, etc.). Frame rate is of primary concern, from the human factors standpoint, because of its causal relationship with flicker. The recommendations made for minimum refresh rate are:

(1) TUB--50 Hz.
(2) DIN--50 Hz.

(3) U of L--50 to 60 Hz for normal ambient light conditions.
(4) DCIEM--60 frames per second.
(5) VDT--50 to 60 Hz.
(6) EG&G--60 Hz, except when very low level ambient lighting exists; then 30 Hz interlaced is acceptable with long persistence phosphors, as long as no perceptual flicker can be detected.

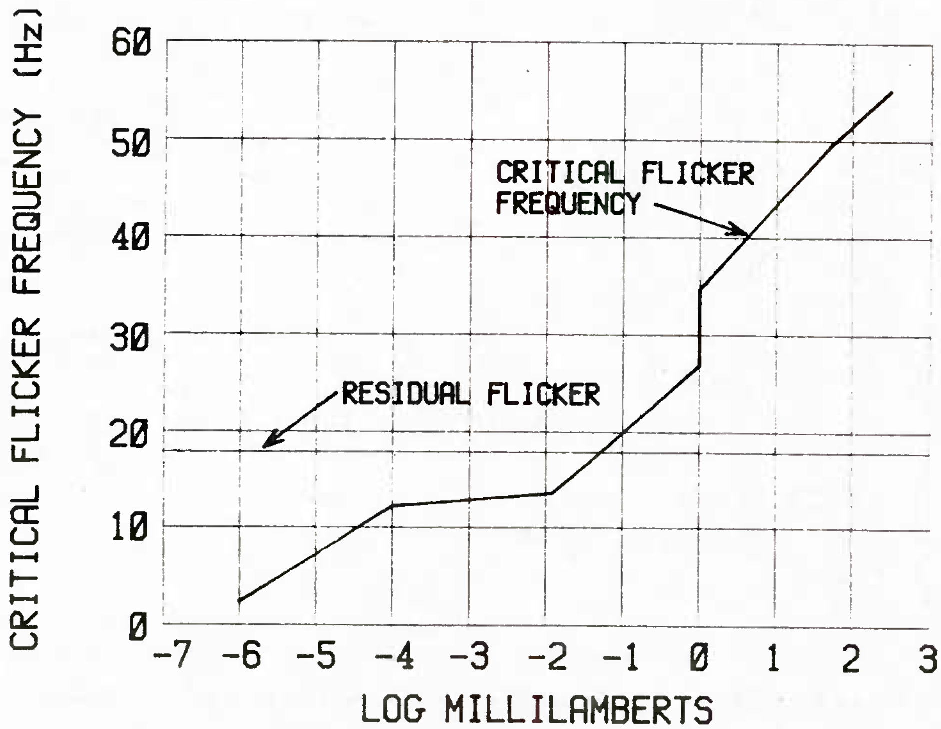


Figure 24. Critical flicker frequency at various brightness levels (Stevens, 1951).

EG&G pointed out that the purpose of these recommendations is to provide a flicker-free display. Since several factors contribute to the perception of flicker--refresh rate being only one--it would be more appropriate to state a functional requirement (i.e., that the display should not appear to flicker under specified luminance settings and ambient light conditions).

Jones, Freitag, and Collyer (1974) suggest that, if the frame rate is slow enough to produce flicker, the problem could be counteracted by increasing the interlacing (see paragraph 2.1.t) beyond the customary 2:1 or by employing storage circuitry that enables the same scene to be presented on successive frames. If such changes are unacceptable for design reasons or other considerations, then the field rate (equal to twice the frame rate for a 2:1 interlace) should not fall below the CFF for the display luminances encountered. It is difficult to predict CFF from laboratory data using square-wave pulses because of the nature of the raster-scan process, the characteristics of the particular phosphor used, etc. The general relationship is that flicker will be perceived at higher repetition rates as the average luminance level increases. The likelihood of flicker can thus be reduced by reducing display luminance. A second procedure is to utilize a longer-decay phosphor. This approach is effective only if there is relatively little image motion, because image motion produces smear with a slow phosphor. Carel (1965) presents curves that show CFF for a variety of phosphors and

viewing distance/screen diameter ratios (p). The determination of p is important because CFF increases as p decreases. As a general guide, a frame rate of 30 per second (2:1 interlacing) will not produce flicker if the average display luminance is approximately 10 to 30 fL (34.3 to 103 cd per m^2) and the highlight luminances (comprising a small portion of the total display) do not exceed 150 fL (514 cd per m^2).

o. <u>Gain</u>. Brightness of a viewed image is a function of screen gain. Gain is defined by the following ratio:

$$\text{Gain} = \frac{\text{Luminance (fL)}}{\text{Illumination (fc)}} \quad . \tag{2.7}$$

p. <u>Glare</u>. Glare is the problem of specular (mirror-like) reflections from the first (outer) surface of the display. The following recommendations were made:

(1) EG&G--No glare on CRT screens is permissible.

(2) TUB--Diffusing surface recommended; avoid eye-focusable reflections.

(3) DIN--Antiglare techniques include using diffusing surfaces, micromesh filters, thin film optical coatings, sprays, hoods, and combination filters.

(4) DCIEM--An antireflection treatment is required.

(5) VDT--Order of preference for control of glare: (a) thin film (antireflection) optical coating, (b) diffusing surfaces, (c) polarization filter, and (d) micromesh filter.

(6) SNBOSH--Avoid bright reflections from the screen.

(7) MILSTD--Glare shall be kept to its absolute minimum.

All sources agree that glare should be eliminated if at all possible. Elimination of glare may be impractical under conditions where CRT equipment is portable (e.g., moved from one part of the room to another).

From a display design standpoint, sunlight shining on a phosphor screen represents the most severe ambient lighting condition. The direct effect of this ambient lighting is reduction of the contrast ratio (CR). When the ambient illumination strikes the display at an angle, the CR equation is modified to:

$$CR = \frac{P + Ar}{Ar} \tag{2.8}$$

where

P = Maximum luminance of the display in fL (not including reflected light).
A = Ambient luminance measured at the phosphor with a diffuse reflector in fL.
r = Coefficient of reflectivity, a coefficient of angle of incidence.

q. Grey scale. The rendition of tones or shades of grey in the gamut from black to white. In normal practice, grey shades are defined as luminance levels related by the square root of 2 or 1.414 ($\sqrt{2}$). The dynamic luminance range within an image must be 32:1 for a 10-step grey scale, since $(\sqrt{2})^{10} = 2^5 = 32$ (Altman et al., 1968).

The contrast or display brightness required for an observer to distinguish grey levels will be affected by image size, visual dwell time, and the brightness difference between the ambient illumination and display brightness. The luminance requirements for any given number of successive grey shades can be calculated based upon the visual angle subtended by the image, the background luminance, and the contrast ratio of a given display. By computing the requirements of each adjacent luminance level, the dynamic range needed can be calculated for any number of grey shades.

r. Hertz (Hz). Cycle per second.

s. Illumination, ambient. Illumination for a viewing area should not be excessively brighter or darker than that of the immediate display surrounds to avoid loss in the observer's contrast sensitivity. Performance is further influenced by surround reflectance. Darker surrounds can require significantly more illumination than light surrounds for the same visual performance (Ozkaptan et al., 1968). Table 4 presents the optimum ambient illumination for various situations. EG&G recommendations are:

(1) BRN--150 to 720 lx.

(2) TUB--50 lx.

(3) DIN--300 to 500 lx for work stations with negative-image (light symbols on a dark background) displays, 500 lx minimum for work stations with positive-image displays, 200 lx if display surface is tilted 20 degrees.

(4) U of L--500 to 750 lx.

(5) DCIEM--50 to 100 fc.

(6) VDT--300 to 500 lx.

(7) SNBOSH--200 to 300 lx.

(8) MILSTD--Whatever is appropriate.

EG&E (Banks, Gertman, & Peterson, 1982) comments are:

(1) One would expect ambient light level recommendations to be rather consistent. However, different objectives have been addressed, and that has resulted in some variation in the recommended ranges of ambient light levels.

(2) The intent of the SNBOSH recommmendation is to provide an ambient light environment that is satisfactory for many tasks and to permit a display contrast ratio of about a 15:1 or more. The SNBOSH directive also states that supplementary lighting for source documents (and the like) may be used at the work station.

Table 4

Levels of Illumination Currently Recommended for Specific Visual Tasks
(Taken from Meister & Sullivan, 1969)

Work Area or Task	Footcandles on Task[a]
Assembly and Repair	
Rough easy seeing (installing chassis in rack)	30
Rough difficult seeing (component replacement)	50
Medium (soldering wires to a connector)	100
Fine (electronic micromodules)	500
Bench Work	
Rough easy seeing	30
Rough difficult seeing	50
Medium	100
Fine	500
Control rooms	50
Console surfaces and/or panels	50
Dials, gages, meters, and scales[b] (on face)	50
Equipment racks and panels	30
Emergency lighting[c]	3
Inspection	
Ordinary	50
Difficult	100
Very difficult	500
Office Work	
Cartography and detailed drafting.	200
Accounting, auditing, tubulating, bookkeeping, business machine operation, reading poor reproductions, and rough layout drafting.	150
Regular office work--reading good reproductions, reading or transcribing handwriting in hard pencil or on poor paper, active filing, etc.	100
Reading or transcribing handwriting in ink or medium pencil on good quality paper and intermittent filing.	70
Reading high-contrast or well-printed material, tasks, and areas not involving critical or prolonged seeing, such as conferring and interviewing.	30
Testing	
General	50
Electrical equipment or equivalent	100
Radar displays (plan position indicator)	0.1[d]
Switch boards	50
Information boards	50
Teletype machines	150

[a] Minimum level for the task at any time.

[b] A steel scale with 1/64-inch divisions requires 180 fc of light for easy reading.

[c] Level measured 30 inches above floor.

[d] Maximum on task at any time for cathode-ray tube using P7 phosphor.

(3) The U of L and DCIEM recommendations are intended to provide adequate illumination for reading the source document and to follow general illumination recommendations for that type of task. There really is not a conflict between these recommendations and the SNBOSH recommendation.

(4) The German Illuminating Engineering Standard, DIN 5035, requires a fairly even illumination over the work station surface. It would be difficult to use supplementary lighting at a work station and comply with that standard. The 200 lx ambient light level recommended for work stations with a tilted display surface would seem unreasonably low if the task at the terminal also included the reading of source documents (p. 15).

The most obvious way of controlling ambient light is by means of filters. Where a sunshade is not possible and controlling the ambient conditions is not practical, a more sophisticated method is available for improving the contrast ratio of a display. It involves the use of limited acceptance angle filters or neutral density filters based on polarization principles (Humes & Bauerschmidt, 1968).

Another troublesome aspect of ambient illumination incident to displays is the problem of glare. Thresholds for target perception become higher as glare luminance increases, area of glare source increases, distance between glare source and display decreases, and image or display size is decreased. Figure 25 shows the relationship between image luminance and glare luminance.

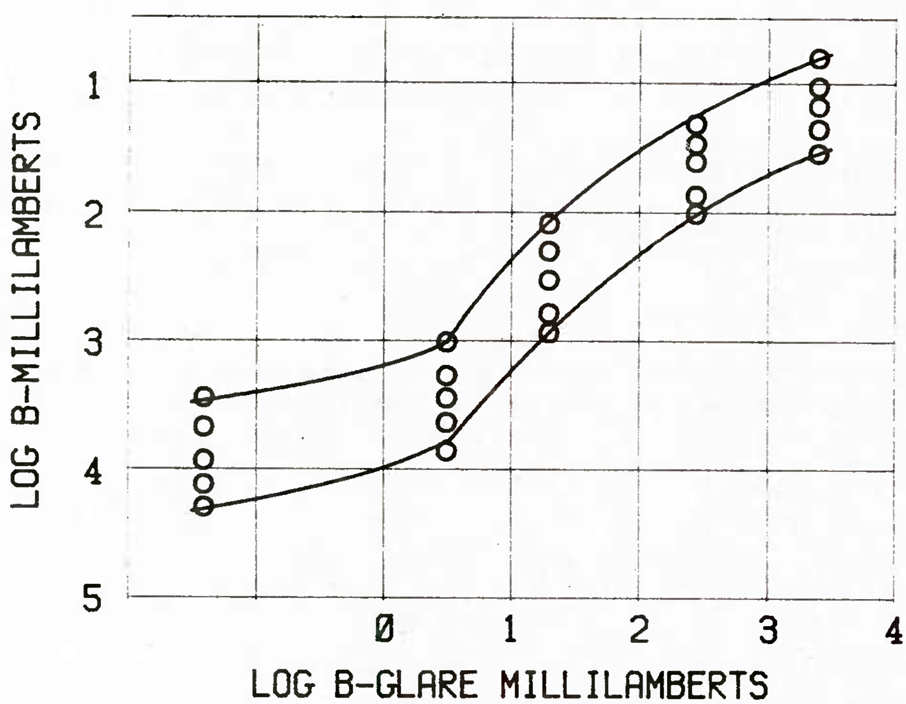


Figure 25. Relationship between image threshold luminance and glare luminance (thresholds increase as glare luminance is increased) (Wolf & Zigler, 1959).

t. Interlacing. A technique for eliminating display flicker without increasing the date rate, thus conserving bandwidth. TV systems normally employ an information update rate of 30 frames per second. At this frame rate, flicker would be noticeable at typical display luminance levels. To increase the frame rate, the scanning spot would have to move across the display at a faster rate and, therefore, to maintain the same horizontal resolution, the bandwidth would need to be increased.

To maintain frame rate at 30 frames per second and avoid flicker, the standard procedure is to cause the CRT beam to write every other line and then start at the beginning to fill in the "spaces." This technique, which is called 2:1 interlacing, results in a field rate of 60 per second, while the information update rate is still only 30 per second. Although each individual line is still flashing 30 times per second, at normal viewing distances, flicker is imperceptible because the resolution of the eye is sufficiently low at such a high spatial frequency.

Although an interlace ratio of 2:1 is standard, in some applications it could be desirable to use a higher ratio. For example, if a CRT were designated for use in a high ambient illumination environment, the display luminance might be high enough to cause flicker at a rate of 60 fields per second. By using a 3:1 interlace, a 90 per second field rate would be obtained. As another example, if the scene is changing slowly so that the information update rate of 30 per second is not needed, it might be desirable to employ a lower frame rate; therefore, the bandwidth could be reduced or resolution improved. At 20 frames per second, a 3:1 interlace would bring the field rate to 60 per second again. In ordinary applications, there would be no advantage to increasing the interlace ratio unless frame rates were simultaneously reduced.

u. Image polarity. Image polarity refers to the nature of the CRT display, either positive (dark symbols on light background) or negative (light on dark). The following recommendations were made:

(1) EG&G--User's choice.
(2) TUB--Positive preferred.
(3) Negative presentations are unfavorable for perception (Rey & Meyer, 1977).

According to Rupp (1981), image polarity is of considerable concern in Europe--presumably less so in this country. A number of reasons exist for preferring positive polarity, although the empirical evidence is dubious on this point. TUB (Cakir et al., 1978) reports a study that indicated the pupillary response mechanism might be stressed if there are frequent refixations between a source document and a negative-image display. However, Rupp (1981) did not find this when he duplicated the TUB study.

v. Lambert (L). A unit of luminance equal to that of a perfectly diffusing and reflecting surface illuminated by a standard candle at a distance of 1 centimeter (cm). One milliLambert (mL), which is 1 thousandth of a Lambert, is very nearly equal to 1 foot-Lambert (fL). One fL is a unit of luminance equal to that of a perfectly diffusing and reflecting surface illuminated by 1 fc. (Conversion factors are given in Table 5.)

w. Lines. The limiting spatial frequency that an optical or photographic system or element can resolve in terms of lines. Resolution is often expressed in terms of lines or line pairs per mm. For example, lines per MHz indicate the horizontal resolution per MHz of bandwidth in TV applications.

Table 5

Conversion Factors for Brightness Units

Units	Foot-Lamberts	Lamberts	Milli-Lamberts	Candles per square-inch (inch-candles)	Candles per square-foot (foot-candles)	Candles per square-centimeter (centimeter-candles)
fL	---	0.001076	1.076	0.00221	0.3183	0.0003426
L	929	---	1,000	2.054	295.7	0.3183
mL	0.929	0.001	---	0.002054	0.3957	0.0003183
c/in^2	452.4	0.4869	486.9	---	144	0.155
c/ft^2	3.142	0.00338	3.38	0.006944	---	0.001076
c/cm^2	2.919	3.142	3,142	6.452	929	---

Note. Value of units (left-hand column) times conversion factor equals value in units shown at top of column.

For a given bandwidth, as the number of scan lines increases, resolution across the raster is improved at the expense of resolution along the raster. In general, the following theoretical relationship holds:

$$\text{Bandwidth} = \frac{\text{(RAS 1) (Rbs 1) (frame rate) (scan line length/raster)}}{1.2} \tag{2.9}$$

where

RAS 1 = Number of TV resolution elements along the scan line,
Rbs 1 = Number of TV resolution elements across the raster (or between the scan lines),
= 0.7 (lines/field) (Interlace ratio), and

0.7 is the assumed Kell factor (Humes & Bauerschmidt, 1968).

Figure 26 represents the several alternate usages of the term "line" as related to display work; care must be taken to define the way in which "line" is being used properly (i.e., in TV work, the scanned line and the intervening blank line are counted as two lines, while, in optical work, the scanned line and the intervening lines are counted as one line pair).

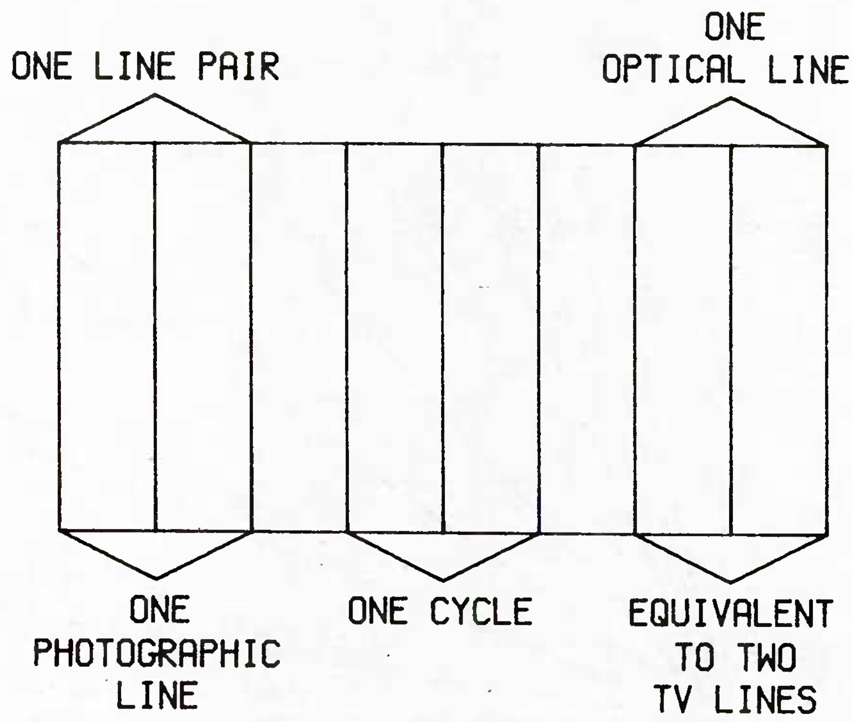


Figure 26. Alternate definitions of "line."

Figure 27 represents a standard resolution target (used to measure the resolving capability of optical systems) and Figure 28 shows the relationship between number of TV lines, frame rate, and bandwidth (D'Aiuto, 1969).

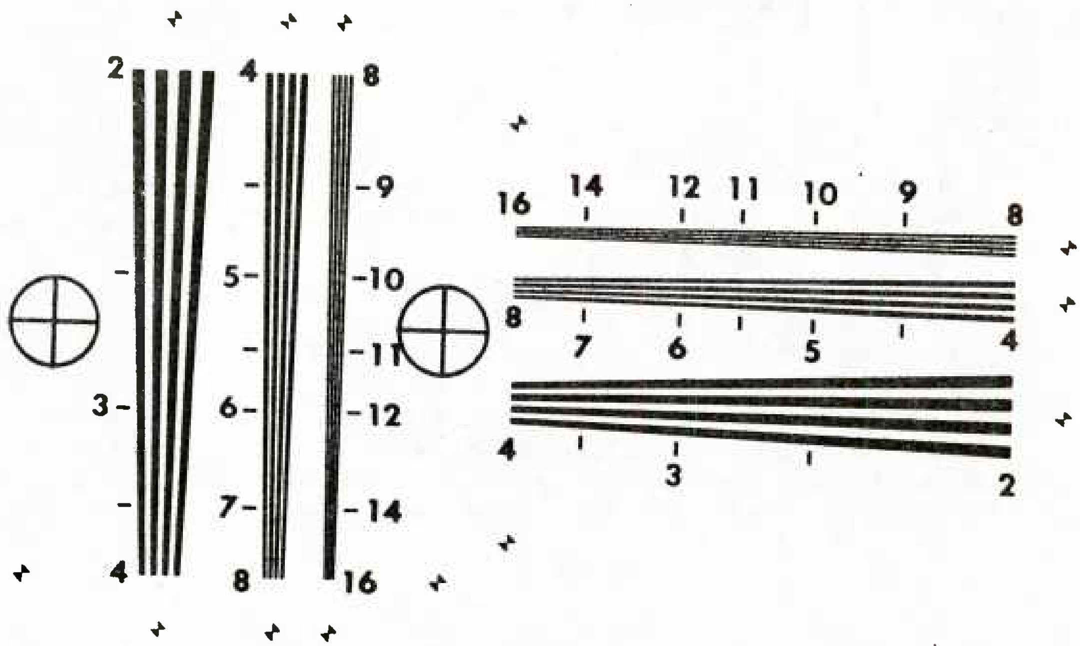


Figure 27. Standard resolution target.

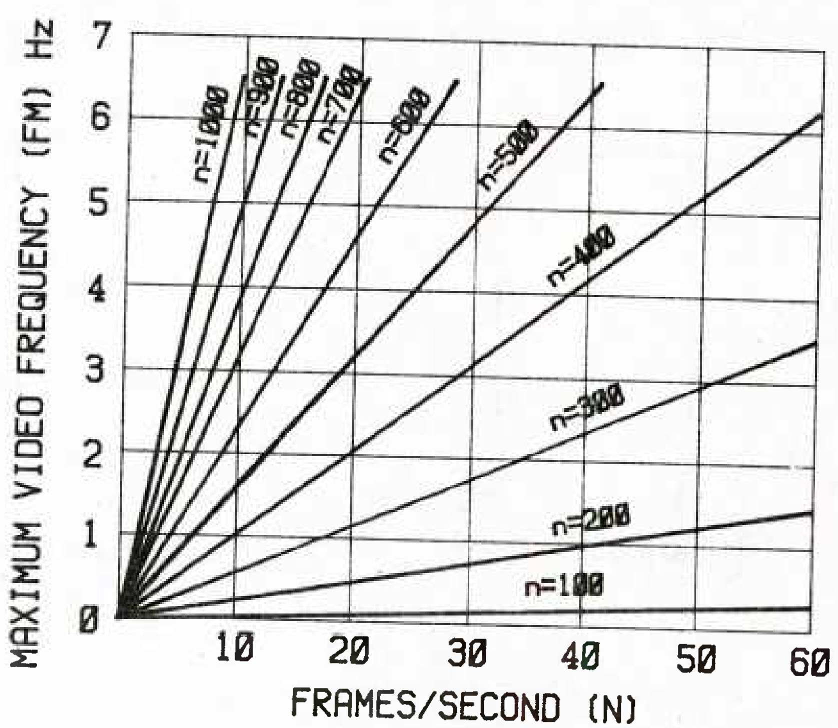


Figure 28a. FM = 0 to 7 Hz and N = 0 to 60 frames per second.

Figure 28. Relationship between frame rate (N), number of TV lines (n), and bandwidth (FM).

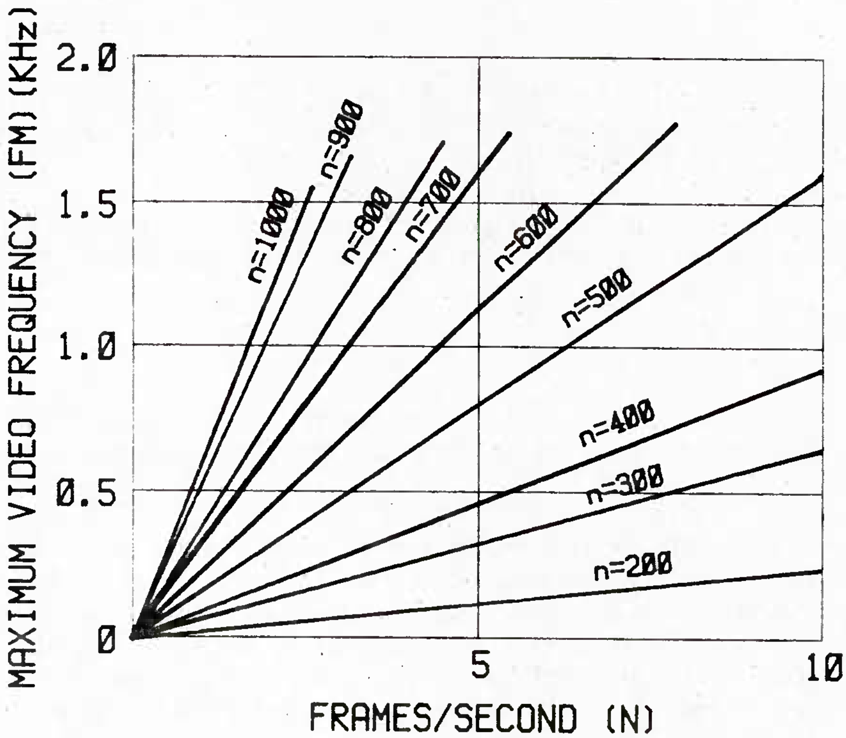


Figure 28b. FM = 0 to 2 KHz and N = 0 to 10 frames per second.

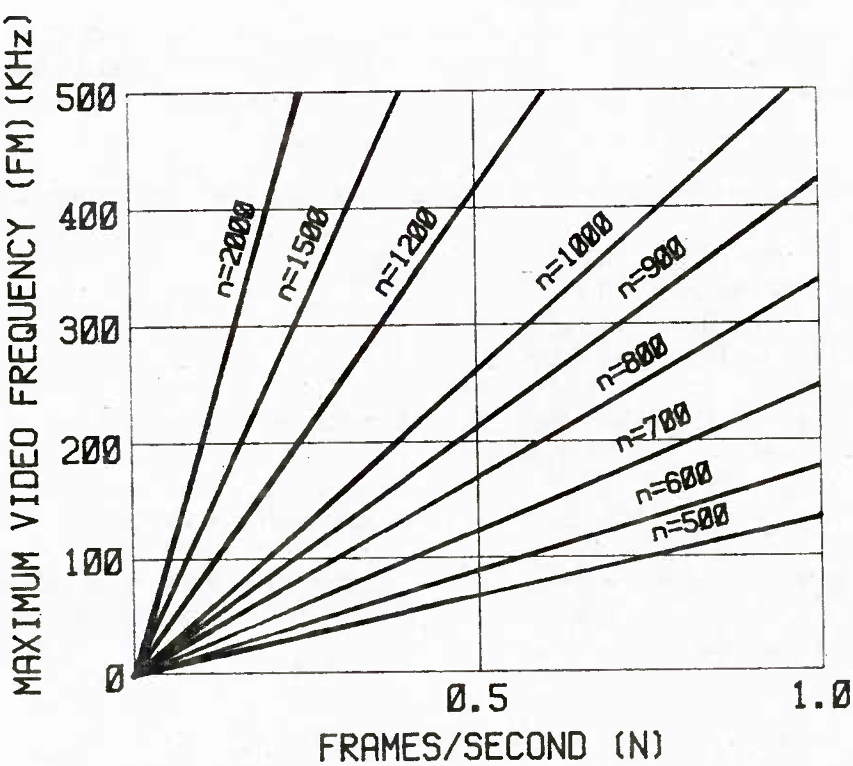


Figure 28c. FM = 0 to 500 KHz and N = 0 to 1.0 frames per second.

x. Luminance (L). The amount of luminous flux emitted in a given direction from an extended source. It is measured in lumens per unit area per steradian and is commonly expressed in foot-Lamberts (fLs).

Brightness (B) is the subjective impression of luminance (L) and under controlled conditions the two are approximately related by a power function

$$B = L^K, \tag{2.10}$$

where K is generally between .3 and .5 for small homogeneous, fields. However, departures from this simple relationship occur for complex pictures between 10 to 100 mL.

Symbol brightness is independent of symbol area because brightness has been shown to be approximately independent of area for areas subtending an angle at the eye greater than 2 minutes, which is much smaller than an individual symbol. It has been shown, however, that, when individual elements (matrix dots) of a symbol subtend less than 2 minutes, legibility (as defined by the accuracy with which observers recognize tachistoscopically presented numerals) depends upon the product of element size and luminance.

Symbol brightness is not affected by brightness of the background (i.e., symbol brightness is independent of contrast).

Brightness does depend, however, upon the sharpness of the edges of the image. This is relevant because of the relatively blurred (compared to hardcopy) symbols on CRTs. A nearly linear positive relationship exists between brightness and sharpness (Gould, 1968).

Standards for screen luminance in viewing motion pictures are:

(1) Minimum—5 fL.
(2) Adequate—10 fL.
(3) Excellent—15 fL.
(4) Maximum—20 fL.

y. Lumen. The basic unit of photometry is equal to the flux produced by a point source of 1 candle within 1 steradian.

z. Megahertz (MHz). Equal to 1 million cycles per second.

aa. Misregistration. Registration is the superimposition of a homomorphic image to form a composite single image. Misregistration is the degree or percent of misalignment of these images and is defined as:

$$\text{Misregistration} = \frac{M - S}{S} \times 100\%, \tag{2.11}$$

where

M = the stroke width of the misregistered image,

S = the stroke width of the perfectly registered character.

By this definition, an image with 0 percent misregistration is completely aligned while an image with 100 percent misregistration represents two distinct images precisely adjacent to each other. Snadowsky, Rizy, and Elias (1964) recommend that misregistration cannot exceed 33 percent under operational conditions without loss of performance.

bb. Modulation transfer function (MTF). To predict how a system will respond to a pattern, the system's response to the sine wave components comprising the pattern must be known. The MTF is simply a means of describing the sine wave response of the system across a range of frequencies. For example, to determine the MTF of a lens, the lens would be presented with a series of sine wave gratings that would gradually change from broad to narrow stripes. The modulation of each grating can be determined by measuring its luminance at the brightest point (L_{max}) and at its dimmest point (L_{min}). Modulation (M) is then defined as:

$$M = \frac{L_{max} - L_{min}}{L_{max} + L_{min}} \quad . \tag{2.12}$$

The procedure is to measure the modulation of the original grating and the modulation of the grating as imaged by the lens. The modulation transfer for that particular frequency is then expressed as the ratio: M_{image}/M_{object}.

To determine the sine wave response of the human visual system is more complicated because a photometer cannot be used to measure objectively the luminance distribution of an object as perceived by the observer. Instead, it is necessary to employ indirect procedures. Several different kinds of procedures have been employed with the results in general agreement. The greatest sensitivity to spatial frequencies usually occurs in the fovea in the region of 3 to 6 cycles per degree, the higher value being for the higher luminances. A transfer function for the human visual system of the general form shown in Figure 29 is eventually obtained. At each luminance level, the functional values are slightly different, although the shape of the curve remains the same.

The modulation transfer function area (MTFA) shown in Figure 30 is the area between the system MTF and the detection threshold curve of an observer viewing patterns imaged by that system (or under predicted conditions typical of that system). MTFA is a summary measure of image quality that has recently been shown (Snyder, 1972) to be a good predictor of observer performance with line-scanned imagery. It is a way of expressing image quality in relation to the visual requirements of the observer. Although the MTF describes the ability of a system to transmit an image, it says nothing about the quality of that image with regard to the observer. For example, two TV systems with identical MTFs, yet with different gammas or different amounts of noise, may not be identical with respect to observer performance. The MTFA attempts to account for these differences by incorporating a measure of the observer's threshold sensitivity for patterns produced by the system being evaluated.

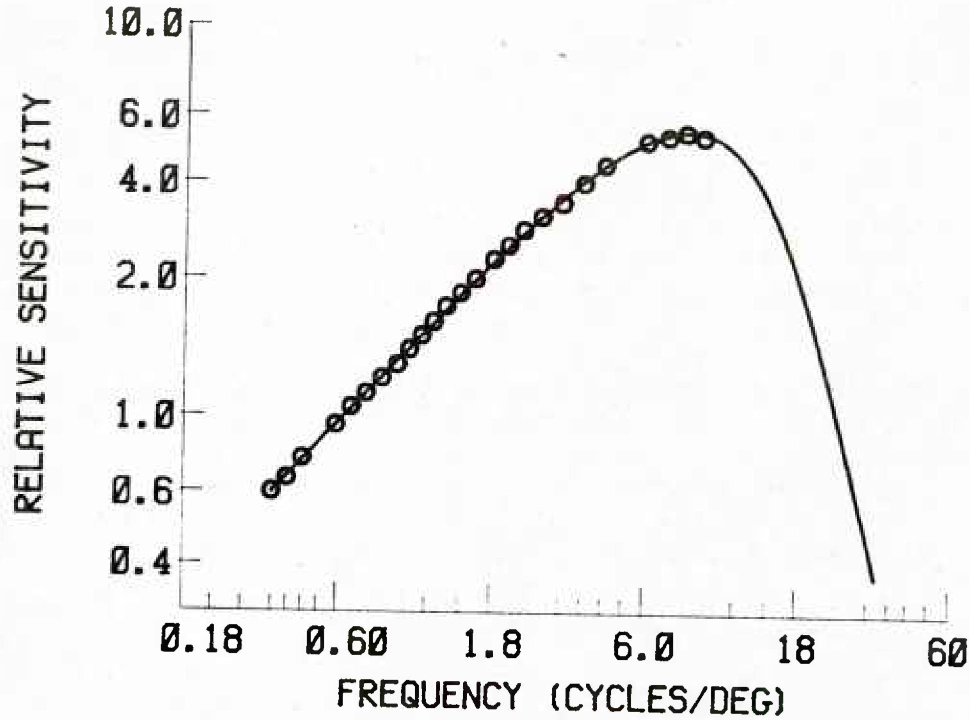


Figure 29. A transfer function for the human visual system. Circles are data points from a contrast matching experiment; the region without circles is based on threshold measures (from Cornsweet, 1970).

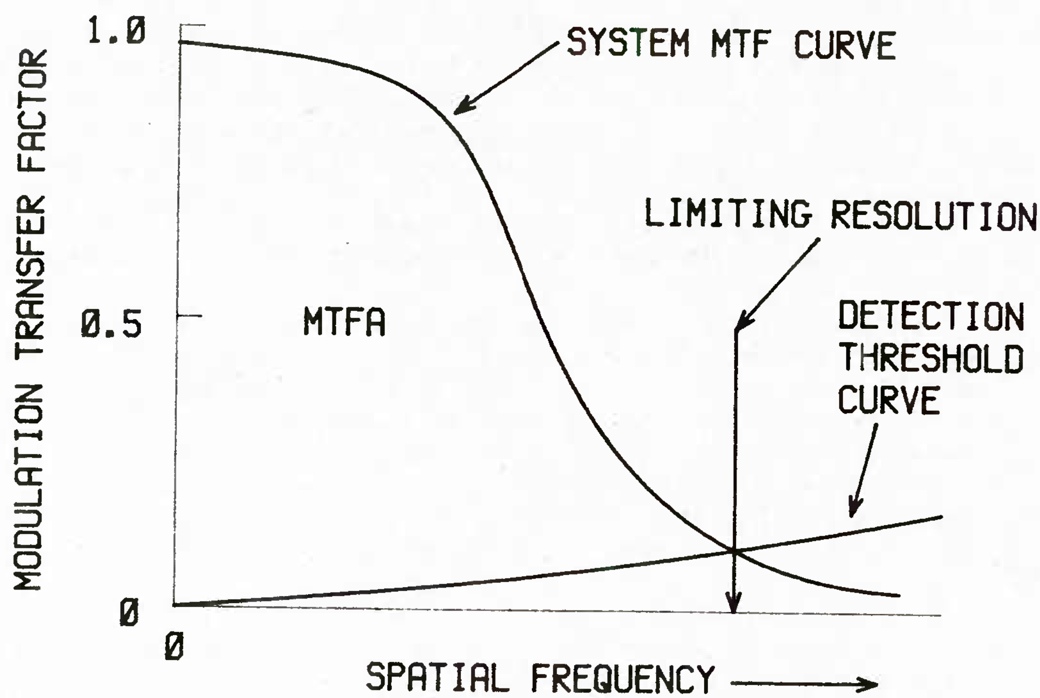


Figure 30. Modulation transfer function area (MTFA) (Snyder, 1972).

System MTF can be determined easily enough according to established procedures. The observers' threshold curve, however, varies with a number of parameters (e.g., luminance, noise, etc.) so that it is difficult to determine other than by testing a number of subjects under the conditions being evaluated; this is one reason that the MTFA is not yet widely employed as an evaluative tool.

cc. Noise. In display systems, noise can manifest itself in several ways. In projected displays such as TV, grain noise or electrical noise is present in every frame; however, frame rate causes the noise to appear to be in motion and changing, therefore affecting the viewer's judgment of resolution and luminance change (Altman et al., 1968).

The detection of a signal in the presence of noise requires that the signal-to-noise ratio (SNR) be equal to or larger than some threshold level (TH):

$$SNR_{TH} = J. \qquad (2.13)$$

The factor J varies with the characteristics of the object to be detected and of the noise. Typically, J = 1.52 for a point source, 4.3 for a disc in random noise, and approximately 3.0 for a bar type resolution pattern. Thus, the visibility of a bar type resolution pattern requires at least 3:1 SNR or 9.5 dB (20 log 3), peak signal to rms noise for a single presentation (Altman et al., 1968). In multiple look situations, the ratio is somewhat lower with 6 dB presently being used operationally.

Display quality and hence performance are characterized by the ratio of maximum value of the video signal to the rms noise. An SNR of 30:1 is considered good quality for television systems (Bogatov, 1966) with 35 dB considered "noise free" by most TV viewing standards (Humes & Bauerschmidt, 1968). SNR is derived electronically and, therefore, cannot be used very well as an index of image quality.

The concept of the display signal-to-noise ratio (SNR_{DI}) is an attempt in target acquisition research to provide a summary measure of image quality that can be used to predict the visibility of a specific target imaged on a display. The basic approach is to combine the interrelated factors that affect observer performance into an equation that system designers can use to calculate whether particular targets can be detected, recognized, or identified. The equation starts with the video signal-to-noise ratio (SNR_V), which can be measured electronically, prior to being inputted to the display, as the peak-to-peak target signal divided by the rms noise level. SNR_V is then modified to include bandwidth, visual temporal integration time, the size of the target as imaged on the photosurface, and the size of the photosurface itself. The resulting formulation is:

$$SNR_{DI} = \left[2t\ \Delta f_v\ (a/A)\right]^{1/2} \cdot SNR_V \qquad (2.14)$$

where

SNR_{DI} = image signal-to-noise ratio on a hypothetically perfect display,
t = visual integration time (assumed to be 0.1 second),
Δf_v = video bandwidth in Hz,
a = target image area at photosurface,
A = total area of photosurface,
SNR_V = video signal-to-noise ratio.

This equation shows that increasing the size of the target imaged on the photosurface decreases SNR_V and maintains the same SNR_{DI}. Threshold SNR_{DI} is very nearly a constant over a considerable range of target sizes.

The SNR_{DI} approach is used to calculate image quality for a target of a specified size; it is not an overall measure like the MTFA, which describes image quality over a range of spatial frequencies. The SNR_{DI} is calculated for the particular frequency of interest, which is one of its virtues for practical applications. It may be used, for example, as a means of calculating the TV camera field of view and, hence, the required focal length to make the image of a ship large enough to be detected at a particular distance.

Rosell and Willson (1973) found that, for aperiodic targets such as single rectangles and squares, SNR_{DI} was a reliable predictor of performance; as the size of the targets was changed considerably, the SNR_{DI} required for .50 probability of detection stayed very nearly the same.

Table 6 presents the results of experiments and the best estimate currently available for the SNR_{DI} required for various levels of discrimination. The third column presents the bar pattern density used to calculate SNR_{DI}; the remaining four columns present required SNR_{DI} for targets of different sizes, expressed as the spatial frequency of the equivalent bar pattern. The threshold values given are for 0.50 probability of correct performance; to convert to another probability use Figure 31. As either the discrimination level or the background complexity increases, the variability in SNR_{DI} also increases; hence, accuracy of performance prediction decreases. SNR_{DI} is potentially a very useful approach to specifying and predicting image quality. For instance, if designers can make some assumptions about target size, target and background reflectances, level of scene irradiance, and atmospheric transmission factors, they can calculate whether a particular sensor field of view would be adequate for identifying the target at a particular range, when those system parameters that would determine SNR_V are known. This approach could also be used to compare the performance of different sensors in specific situations.

dd. Phosphor. An inorganic material exhibiting a nonthermal emission of visible electromagnetic radiation upon excitation. Phosphors used for screens of CRTs have two important characteristics, color and persistence, that are used to define the phosphor. Table 15 presents a list of currently available phosphors and their characteristics.

P31, P4, and P7, are probably the most commonly used phosphors because of the needed frame rate and required persistence characteristics. P7 is used in a high percentage of CRT sonars. Inquiry or alphanumeric displays use the P4 and P31 phosphors almost exclusively. Phosphors that emit maximally in the middle of the visible spectrum are preferable to those that emit at the blue end of the spectrum because human visual sensitivity is much higher for green than for blue light.

Table 6

Best Estimate of Threshold SNR_{DI} for Detection, Recognition, and Identification of Images
(From Rosell & Willson, 1973)

Discrimination	Background	K_d [b] TV Lines per Minimum Dimension	Threshold SNR_{DI} for a Single Bar of Spatial Frequency (in lines/picture height) Equal to			
			100	300	500	700
Detection	Uniform[a]	1	2.8	2.8	2.8	2.8
Detection	Clutter	2	4.8	2.9	2.5	2.5
Recognition	Uniform	8	4.8	2.9	2.5	2.5
Recognition	Clutter	8	6.4	3.9	3.4	3.4
Identification	Uniform	13	5.8	3.6	3.0	3.0

[a]Treated as an aperiodic object.

[b]Johnson's criterion.

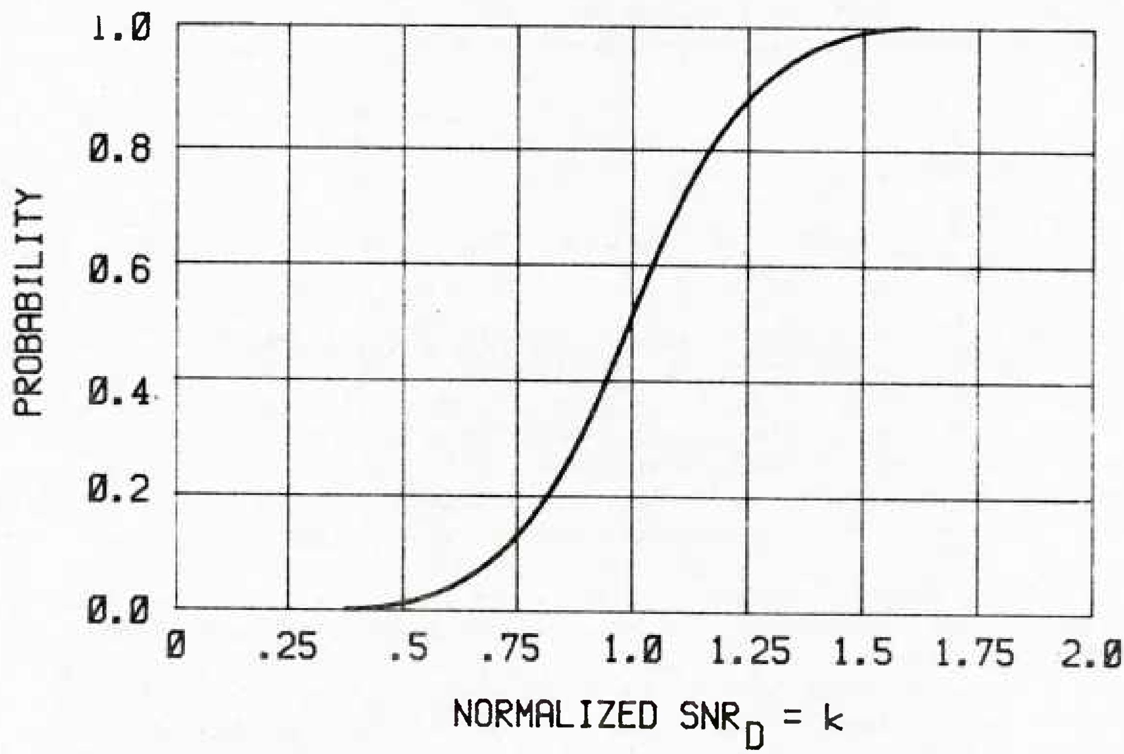


Figure 31. Probability versus normalized SNR. For any probability value, obtain SNR_{DI} from Table 6 for 50 percent probability. Find value of k for desired probability and multiply value of SNR_{DI} by k to obtain new value of SNR_{DI} required (from Rosell & Willson, 1973).

EG&G makes the following recommendations:

(1) TUB--P4, P31.

(2) U of L--Medium persistence.

(3) DCIEM--Short persistence.

(4) EG&G--The use of high-persistence phosphors is not recommended due to "tracking effects" (smearing) and reduced contrast control. However, if low ambient light environments are desirable and negligible tracking or flicker can be detected, high persistence phosphors are acceptable, but only on plot/graph displays.

(5) TUB assumes a negative correlation between phosphor persistence and phosphor life; hence, short-persistence phosphors have been recommended even though they are more susceptible to flicker. In actuality, there is little correlation between phosphor persistence and phosphor life; P1 and P39 have persistences long enough to minimize flicker perception significantly, while having considerably longer life expectancies than either P4 or P31.

(6) U of L points out that short-persistence phosphors are more susceptible to the perception of image scintillation (jitter) and that long persistence phosphors may leave a smear of the previous image when the display is updated; hence, they recommend a medium-persistence phosphor as the best compromise.

ee. Phophorescence. Luminescence having a persistence longer than 10^{-8} second, which is the residual emittance following flourescence of a phosphor. Residual brightness and persistence are measures of phosphorescence.

ff. Raster. A uniform pattern of lines produced by scanning a screen in a rectilinear manner.

gg. Registration. The superimposing (placing side by side) of multiple images to form a composite single image. Misregistration is failure to overlap the images correctly. Misregistration may be caused by geometric distortion or by improper direction or alignment of the system. Registration of 0 percent indicates completely accurate positioning of images; with stroke width misregistration of 100 percent, the images are just adjacent to each other. Electromechanical systems are capable of 0.1 percent of screen-width registration accuracy, as are projection CRT systems.

hh. Resolution. Sherr (1979) defines spot reduction as "the smallest discernable or measurable detail in a visual presentation" (p. 9). Spot resolution in CRT-type displays is determined by the size of a focused electron beam spot on the phosphor screen. This spot is usually generated by a 10 microampere beam current in accelerating voltage; in color tubes, phosphor-grain size controls minimum spot size. Spot shape (controlled by gun type) affects size and, therefore, has an effect upon resolution. Spot size is generally expressed according to the "compressed raster" definition; that is, the distance between two points on opposite sides of the spot center at which the brightness is half that of the center (Wolf Research & Development, Inc., 1968). In displays where the spot is scanned in a rectilinear manner producing a raster scan pattern, resolution is expressed by the number of line-space pairs (or lines in photo-optical work) per unit linear dimension (see Figure 26). There are many definitions of spot resolution. Spot resolution is also a different type of resolution than minimal separable resolution, the ability to see

two objects as two instead of one. Several sources, in particular Carel (1965) and Semple, Heapy, Conway, and Burnette (1971), discuss resolution in great detail.

Television systems are generally designed to have equal horizontal and vertical resolution. Horizontal resolution is defined as the maximum number of line-space pairs that can be resolved within a horizontal expanse of raster equal to one picture height. Horizontal resolution is primarily determined by the bandwidth, line scan rate, and display aspect ratio. Vertical resolution is defined as the maximum number of line-space pairs that can be visually resolved or in line-pairs per picture height. Actual vertical resolution (for an interlaced television system) equals the number of active lines per frame times .7 (the Kell factor; i.e., for a total number of 1850 active lines, the vertical resolution is 1290 TV lines). Vertical resolution is not affected by bandwidth.

In normal room light, the average eye can, with difficulty, discriminate 40 parallel lines alternating black and white (80 TV lines) per degree of arc resolved at the eye. From a fixed point, a user can see a TV display that subtends 50 degrees at the eye; this permits the eye to discriminate 2000 lines of detail on the display. Figure 32 presents the effect of resolution on recognition performance.

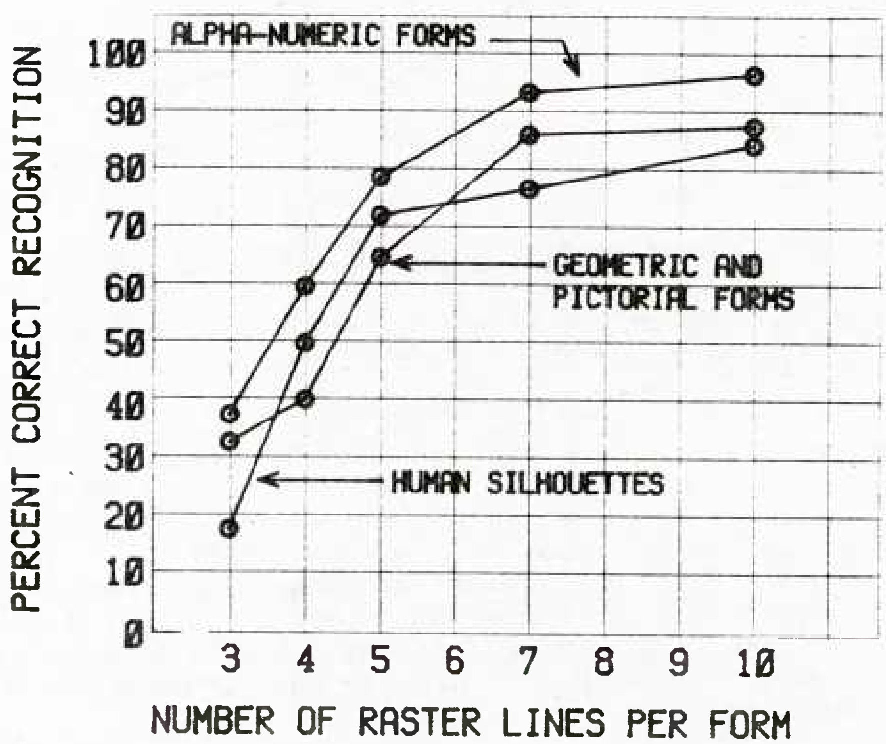


Figure 32. Recognition of various classes of forms as a function of the number of active raster lines that composed the forms (Baker & Nicholson, 1967).

Erickson and Main (1966) found that patterns made up of at least 6 scan lines could be located 100 percent of the time, but that, for 80 percent identification accuracy, 20 scan lines were required. Erickson, Main, and Burge (1967) found with a different monitor that 90 percent identification accuracy was obtained with 12 scan lines per symbol.

Figure 33 summarizes symbol legibility (80%, 90%, and 95% correct) as a function of angular subtense and number of scan lines per symbol. This figure suggests that, over a certain range of values, a tradeoff exists between angular size and number of lines across the target. If the target becomes smaller in angular subtense, the same level of performance can be achieved by increasing the number of scan lines across it.

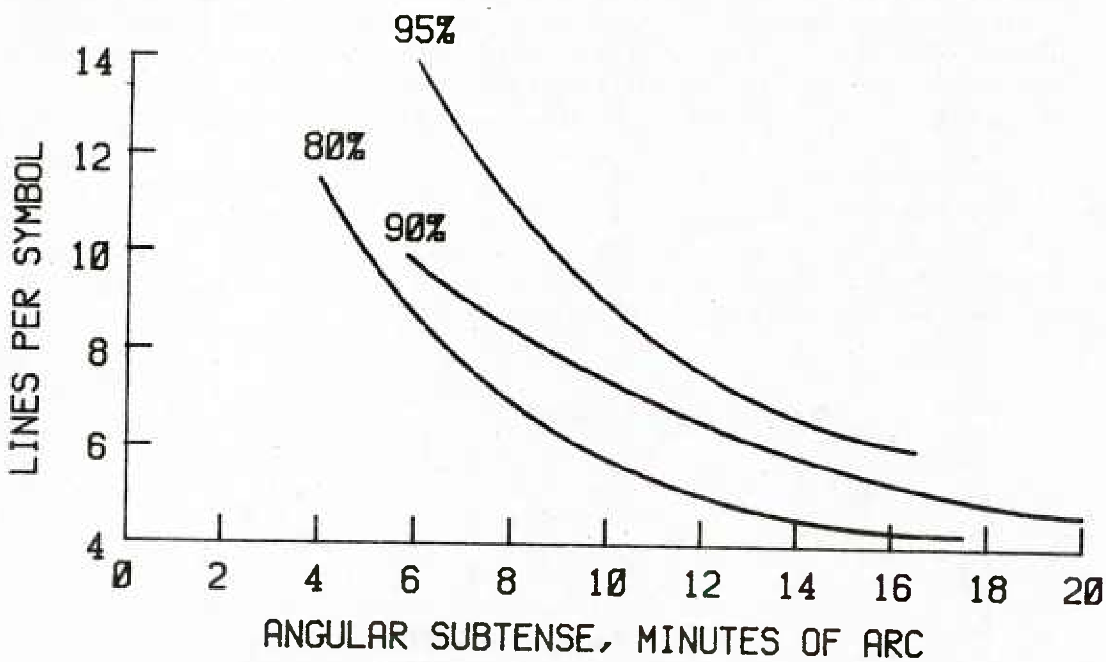


Figure 33. Summary of symbol legibility performance at 80, 90, and 95 percent correct (from Hemingway & Erickson, 1969).

Figure 33 describes abstract stimuli. Studies performed with photographs of realistic stimuli (e.g., military vehicles, storage tanks, aircraft, etc.) found that, for high probability of correct identification, vehicles have to subtend 14 minutes of arc and have at least 10 scan lines (Erickson & Hemingway (1970); for 90 percent correct identification, between 7 to 10 scan lines (Brainard, Hanford, & Marshall, 1965); for 80 percent identification accuracy, 12 scan lines (Levine, Jauer, & Kozlowski, 1970). Increases to 20 scan lines did not improve performance. Self (1971) suggests 15 to 20 scan lines across the target for identifying unbriefed targets. If the system is moderately noisy, this estimate may go to more than 30 scan lines.

The Target Acquisition Working Group (1972) summarizes estimated line numbers for three different mission conditions and three levels of target discrimination (Table 7).

Snyder (1980), after reviewing the literature, states that "in general, the extensive literature relating CRT resolution to observer performance shows that performance increases with increasing resolution, to some high resolution level at which observer performance reaches a practical asymptote" (p. 280). Humes and Bauerschmidt (1968) found that percent of correct recognitions increased as the number of lines increased from 729 to 1029 lines (see Figures 34 and 35). Carel (1965) recommends the use of a 1000 line raster in airborne displays, which Jones et al., (1974) feel is a little high.

Table 7

Estimated Required Number of Scan Lines Across Target as a Function of Mission and Level of Discrimination
(From Target Acquisition Working Group, 1972)

Condition	Required Number of Scan Lines		
	Detection	Recognition	Identification
1. Accurate mission briefing, target location known, no friendlies in area, few clutter objects, accurate aircraft NAV systems.	4	8	8
2. Accurate mission briefing, target location not precisely known, clutter objects present.	6	10	16
3. Reconnaissance/surveillance, friendlies in area, target location not precisely known, clutter objects present.	6	15	20

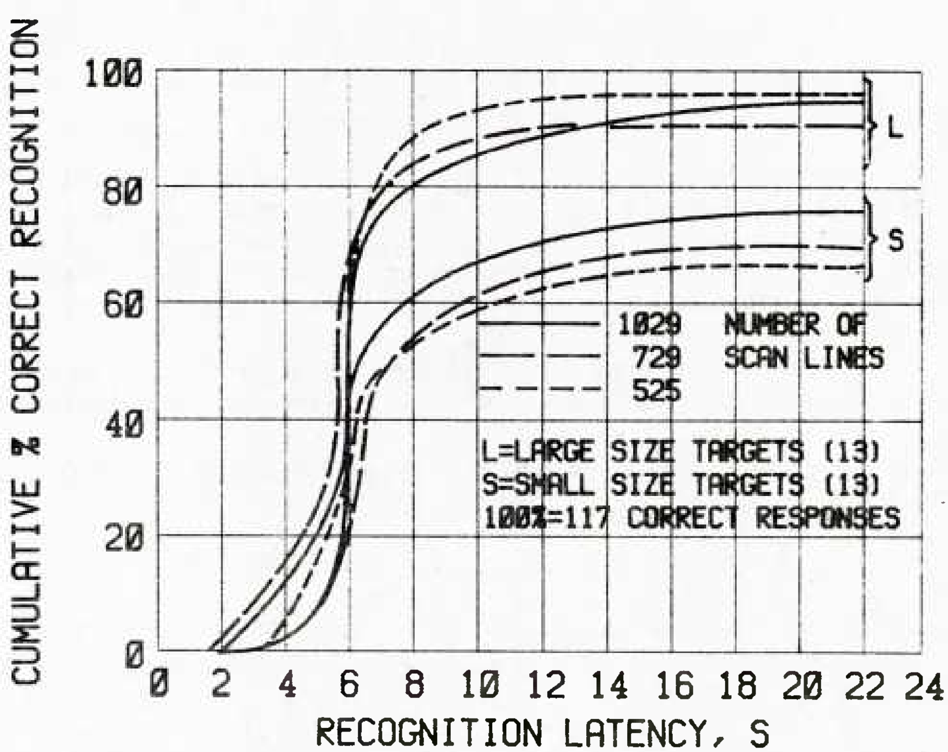


Figure 34. Recognition latency for 525, 729, and 1029 line television systems (from Humes & Bauerschmidt, 1968).

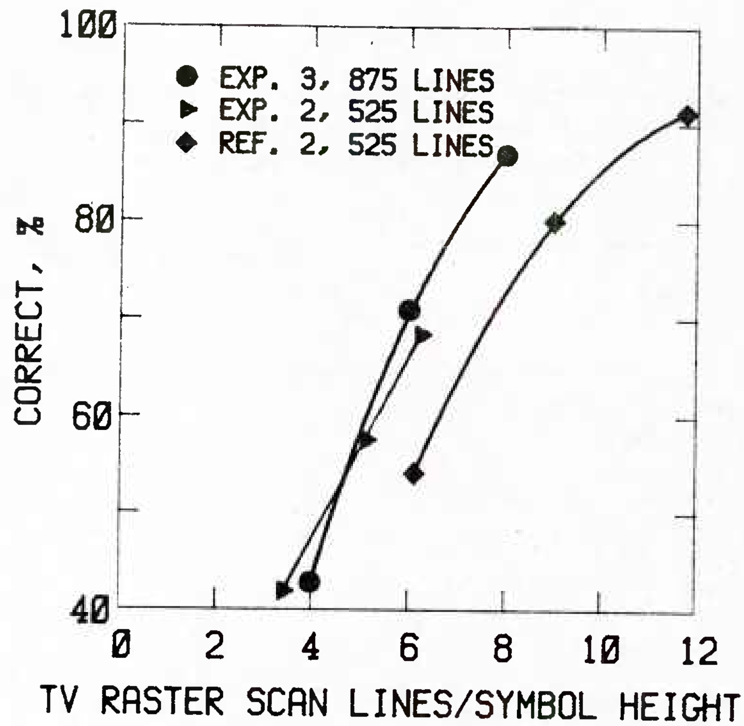


Figure 35. Effects of display raster lines and number of raster lines intersecting target on symbol recognition (from Erickson, Linton, & Hemingway, 1968).

Most alphanumeric and graphic CRT devices presently in use use character heights that subtend at least 12 to 15 minutes of arc at a 30-inch viewing distance (Gould, 1968).

ii. Response time (display generation). The time from initiation of computer output until the complete display is available to the user. At most, 1 to 2 seconds is desirable. Response time is the major, if not the only, justification for automating display systems. The faster a requested display becomes available upon request, the greater is the impact that the display has on systems operations.

Recommendations for system response times as a function of individual activities in using a CRT display (e.g., video display terminal) are shown in Tables 8 and 9.

jj. Steradian (ω). The unit solid angle formed by a cone of radiation emanating from a point source.

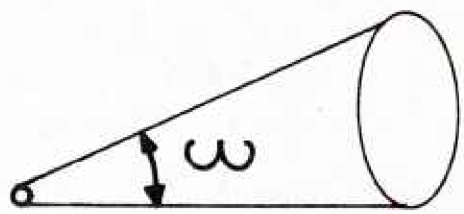


Table 8

System Response Times as Function of System Recognized Activity
(Modified by Banks et al. (1982) from Engle & Granda (1975))

System Interpretation	Response Time Definition	Maximum Acceptable Response Time (s)
Key response	Key depression until positive response; for example, "click"	0.1
Key print	Key depression until appearance of character	0.2
Page turn	End of request until first few lines are visible	1.0
Page scan	End of request until text begins to scroll	0.5
SY entry	From selection of field until visual verification	0.2
Function selection	From selection of command until response	2.0
Pointing	From input of point to display of point	0.2
Sketching	From input of point to display of line	0.2
Local update	Change to image using local data base; for example, new menu list from display buffer	0.5
Host update	Change where data are at host in readily accessible form; for example, a scale change of existing image	2.0
File update	Image update requires an access to a host file	10.0
Inquiry simple	From command until display of a commonly used message	2.0
Complex	Response message, seldom used calculations in graphic form	3.0 10.0
Error feedback	From entry of input until error message appears	1.0

Table 9

System Response Times as Function of User Activity
(Adapted by Banks et al. (1982) from Miller (1968))

User Activity	Maximum Response Time(s)
1. Control activation (for example, keyboard entry)	0.1
2. System activation (system initialization)	3.0
3. Request for given service:	
Simple	2.0
Complex	5.0
Loading and restart	15-30
4. Error feedback (following completion of input)	2-4
5. Response to ID	2.0
6. Information on next procedure	5.0
7. Response to simple inquiry from list	2.0
8. Response to simple status inquiry	2.0
9. Response to complex inquiry in table form	2-4
10. Request for next page	0.5-1
11. Response to "Execute Problem"	0.5-1
12. Lightpen entries	1.0
13. Drawings with lightpens	0.1
14. Response to complex inquiry in graphic form	2-10
15. Response to dynamic modeling	2-5
16. Response to graphic manipulation	2.0
17. Response to user intervention in automatic process	4.0

kk. Uniformity. Uniformity can be defined best in terms of nonuniformity. Three types of nonuniformity can be meaningfully distinguished (Goede, 1978): (1) Large area nonuniformity is a gradual change in luminance (or color) from one area of a display to another such as center-to-edge or edge-to-edge comparisons and gradients, (2) small area nonuniformity pertains to element-to-element changes in luminance or color over small areas, and (3) edge discontinuity refers to changes in luminance or color over an extended boundary.

The effect of lack of uniformity is to reduce operator performance although specific data are lacking. Farrell and Booth (1975) claim that a linear drop in luminance from center to edge of a rear projection display of two-thirds is tolerable and that a gradual brightness falloff of 50 percent will normally appear quite uniform. As a result, they recommend that luminance variation across normally used portions of the display be limited to 50 percent.

For small area nonuniformities, Farrell and Booth (1975) recommend limitations of 10 percent across small portions of the display surface, although this is only an educated guess.

11. Visual angle. Angle subtended by the viewed object at the eye, as shown in Figure 36.

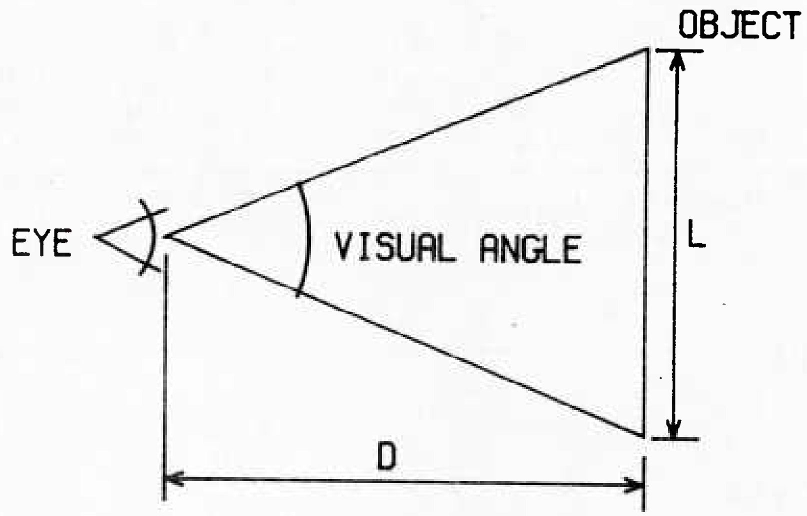


Figure 36. Definition of visual angle.

Visual angle (minutes of arc) = 2 arctan L/2D,

where

L = size of object measured perpendicularly to line of sight and

D = distance from eye to object.

For small angles, tangent ($\alpha/2$) = $\alpha/2$ radians = $\frac{\alpha/2 \text{ degrees}}{57.3} = \frac{\alpha/2 \text{ minutes}}{3438}$.

Thus, $L/2D = \frac{(\alpha/2)}{3438}$ or $\alpha = \frac{3438L}{D}$ for angles of less than 10 degrees. Grether and Baker (1972) use the equation:

$$\text{Visual angle (minutes of arc)} = 3438L/D \tag{2.15}$$

Table 10 represents the conversion of several representative visual angles into symbol sizes (in inches) for several viewing distances.

The probability of detecting an object depends on its size. Figure 37 shows the ogive or cumulative normal curve for one level of luminance and contrast for round uniform discs on a uniform background when object location is known. Consequently, the curve is oversimplified: probabilities vary greatly with luminance and contrast.

Table 10

Conversion of Visual Angles Into Object Sizes

Visual Angle (min. of arc)	Viewing Distance (Inches) 18	28	72	120	240
18	0.09	0.14	0.37	0.62	1.25
15	0.07	0.12	0.31	0.52	1.04
12	0.06	0.09	0.25	0.41	0.83
10	0.05	0.08	0.20	0.34	0.69

Note. Values are $L = \frac{\alpha D}{3438}$.

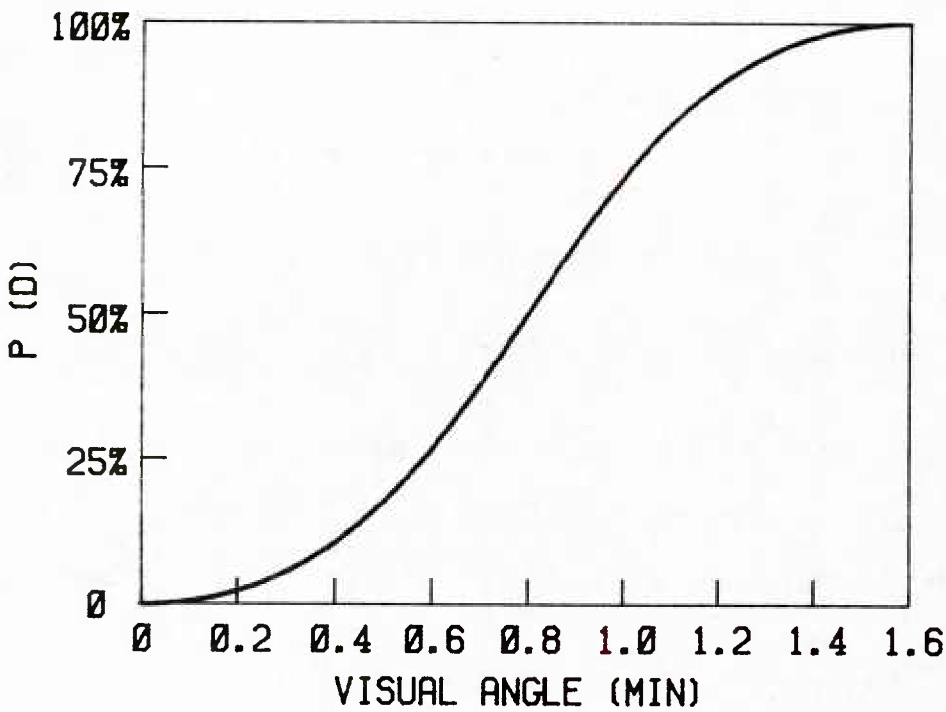


Figure 37. Probability of detection as a function of visual angle (Blackwell, 1946).

2.2 Command/Control Display Functions

Tables 11, 12, and 13 illustrate the variety of command control display requirements and the display types and parameters needed to satisfy these requirements. These are presented not as required answers to display problems but to suggest the variety of solutions possible.

Table 11

Typical Command Control Display Functions

Display Function	Display Content	Display Type	Display Access	Display Rate	Type of Coding
Space surveillance	Tracking stations, launch and orbital data	Console or group display	Called to observer's attention	Real time	Symbology; vehicle type and launch. Line drawings to show trajectory and orbit. Color to differentiate data classes. Alphanumerics; data time.
Air surveillance	Presence of enemy aircraft/missiles; direction of movement	Group display	Called to observer's attention	Real time	Geographic (map); color coding to indicate map zones; symbology for weapon classes; line drawings to indicate tracks.
Missile detection & tracking	Impact prediction	Group display/ alphanumerics	Continuous	Real time	Geographic (map); color coding for predicted impact sites; numeric coding of predictions and summaries. Line drawings to indicate tracks.
Nuclear detonations & radiation	Detonation location	Group display/ alphanumerics	Continuous or called to observer's attention	Real time	Geographic (map); symbology to represent type of burst; color coding to indicate status of site attacked, fallout rate, critical and safe areas.
Targets	Enemy sites to be attacked	Group display/ alphanumerics	On request	On request	Geographic (map); symbology for different target classes; numerics for location.
Weapon and facility status	No., type weapons, locations, committal status, facility (e.g., airbase) status	Console or group display, alphanumerics	On request & continuous	On request & real time	Geographic (map); symbology for different weapon classes, alphanumeric for number of weapons, color coding for availability; line drawings to show geographic position when weapons activated.
Communications	Status of communication terminals	Group display or console/alphanumerics	Briefing	Real time	Color coding to show in-out status. Alphanumerics for terminal identification.
Logistics	Inventories (spares, consumption)	Console/alphanumerics	On request, briefing	Real time	Alphanumerics for identification of type and number; coding for deficiencies.
Enemy order of battle, including status & movement	Number/type units, tracks	Console or group display/alphanumerics	On request or called to attention	On request or real time	Geographic (map); symbology to represent units; alphanumerics for identification of units; color coding to represent status; line drawings for actual and predicted movement.
Own vehicle status and position	Navigation data; battle damage; subsystem availability	Console or group display/alphanumerics	Continuous	Real time	Geographic (map); line drawing for ship track, alphanumerics for course, speed; symbology for subsystems and color coding for subsystem status.
Status of friendly forces, including movement	Type/number of units, tracks	Console or group display/alphanumerics	On request	Real time	Geographic (map); symbology for weather classes; alphanumerics for height, speed; line movement for actual and predicted movement.
Mission planning	Strike order; target assignment; weapons assignment	Console or group display/alphanumerics	Briefing	Real time	Map may be desired as overlay; alphanumerics for units and weapon assignment.

Table 12

Command Control User Requirements Versus Desirable Display Characteristics

User	Number of Characters	Number of Fonts	Special Inputs (light pen, video, etc.)	Special Outputs (hard copy, etc.)	Plotting Capability	Screen Size, in.	Color
Logistics							
Budgeting	2000	1	No	1 per x displays	Bar graphs & tables only	14	No
Process control	500	1	No	1 per x displays	Bar graphs & tables	14	Desirable
Production control	500	1	No	1 per x displays	Bar graphs & tables only	14	Desirable
Inventory management	1000	1	No	Yes	No	14	No
Military							
Photographic and map interpretation	5000		Yes	1 per x displays (low x)	Yes	20	Yes
Cryptography and translation	2000	More than one desirable	No	1 per x displays	No	14	Desirable
Planning and war gaming	Max. poss. (5000 OK)	1	Cursor, light pen	1 per x displays	Desirable	20	Yes
Fleet vehicle location & contents controllers	1000	1	No	Yes	No	14	No
Communications							
Message center operator (alphanumeric)	5000	2	Special devices (maybe)	1 per x displays	No	14	No
Message center operator (pictorial, graphical, data)	5000 or more	1	No	1 per x displays	Yes	20 or more	Yes

Note. Includes alphanumerics and symbols in all cases.

Table 13

Display Requirements by Application

Display Parameter	Air Traffic Control	Command and Control	Guidance and Navigation	Vehicle Stabilization	Communication Status	Message Transmission	Logistic Data	Air Defense	Mission Monitor	Raw Radar	Terrain Avoidance	Reconnaissance	Maintenance	Docking
Data Extraction	O	X	-	-	-	-	X	-	-	X	-	-	X	-
Real Time Presentation	-	O	-	-	-	X	-	O	X	-	-	X	-	-
Prediction (Extrapolation)	-	-	X	-	-	-	-	-	-	-	O	-	X	X
Flexibility (Many Formats)	-	X	-	-	-	-	X	X	X	-	-	X	O	-
Display Bulk (Volume)	X	X	X	X	-	-	-	-	X	-	X	-	-	O
Screen Size	-	X	-	-	-	-	-	-	X	-	-	-	-	
Linearity	X	-	X	-	-	-	-	-	-	-	-	X	-	-
Resolution	X	-	-	-	-	X	-	-	-	X	-	O	-	-
Brightness	X	-	-	-	-	-	-	-	-	X	X	-	-	-
Three-dimensional Display	X	-	X	-	-	-	-	-	-	-	X	-	-	-
Color	-	X	-	-	-	-	-	X	-	-	-	X	-	-
Flicker	-	X	-	-	-	-	-	X	-	O	-	-	-	-
High Information Density	X	X	-	-	-	-	X	-	-	-	-	-	-	-
Legibility	-	-	-	-	-	X	-	-	-	-	-	X	-	-
Update	-	-	-	-	-	-	X	-	X	-	-	-	-	-
Cost	-	-	-	-	-	-	O	-	-	-	-	-	X	-
Scale Problems	-	X	-	-	-	-	-	-	O	-	-	-	-	-
Background Data (Tapes, Charts)	-	X	-	-	-	-	-	X	-	-	-	-	-	-

Legend.

X = Significant for application
O = Critical for application
- = Parameter not important.

2.3 Criteria

The following is a compilation of key performance characteristics and typically accepted numerical values for TV and projected displays.

a. Symbol size--Minimum visual angle 12 to 15 minutes of arc.

b. Resolution (minimum number of TV scan lines per height of symbolic characters for adequate recognition)--10.

c. Stroke width-to-height ratios for symbols--1:6 to 1:10.

d. Character width-to-height ratio--.75; should be closer to 1.0 if display is to be viewed at large acute horizontal angles.

e. Misregistration--Maximum acceptable for additive color mixing: $\pm$ 65 percent of stroke width.

f. Minimum frame rate for display of continuous motion--7-1/2 to 15 frames per second.

g. Geometric distortion. Displacement of any picture element should not exceed 1 to 2 percent (optimum) of picture height from true position. (Acceptable geometric distortion is defined by display application.)

h. Linearity--1 percent acceptable, .2 percent desirable (depending upon application).

i. Display aspect ratio--Commercial TV standards call for 4:3 width-to-height ratio. For greatest legibility, 5:7 or 2:3 are recommended.

j. Acceptable bandwidth--4.0 to 10 MHz.

k. Viewing distance (for individual displays)--18 to 20 inches, also sometimes given as 28 inches, which is average arm reach. For 28 inches, the dimensions of an optimal console display would range from 13 inches above eye level to 20 inches below for the height and from 20 inches on either side of the seat center line for the width.

l. Viewing angle--For console displays, 30 degrees down from horizontal; 15 degrees either side of direct line of sight.

m. Flicker--Display pulse rate should be compatible with CFF for the particular phosphor and driver combination being utilized.

n. Display brightness--Line brightness of 50 fL in normal ambient lighting (lower intensitities will be required for very low ambient light levels).

o. Contrast ratio--90 percent (optimal).

p. Equipment response time--Should range from 2 to 6 seconds; most desirable would be less than 3 seconds at the display station.

SECTION 3

CRT DISPLAY SYSTEMS: PLAN-POSITION-INDICATOR (PPI) DISPLAYS

3.0 CRT DISPLAY SYSTEMS: PLAN-POSITION-INDICATOR (PPI) DISPLAYS

3.1 Introduction

This section describes certain human characteristics and their interrelationships with CRT type display devices. Most of the performance data and the display characteristics referred to in this section are based on plan-position-indicator (PPI) type displays. This is due entirely to the lack of data about human performance on A-scan, B-scan, and other types of devices. The design questions covered in this section deal primarily with the detection function.

Where applicable, the data presented here can be applied with extreme care and judgment to scan types other than PPIs. It should also be noted that almost all our data relative to radar scopes is 20 or more years old.

3.2 How Large Should the PPI Scope Be?

No single recommendation concerning the size of the PPI scope is very safe. All the evidence indicates that optimal size for detection is 7 inches diameter. However, this recommendation applies only when smaller target sizes (2 to 8 mm) are used. When larger target sizes (12 to 16 mm) are used, the advantage of the 7-inch scope disappears (see Figure 38), but the 7-inch scope is still as good as the larger sizes.

Figure 39 shows search time as a function of search area under conditons comparable to real-world display conditions.

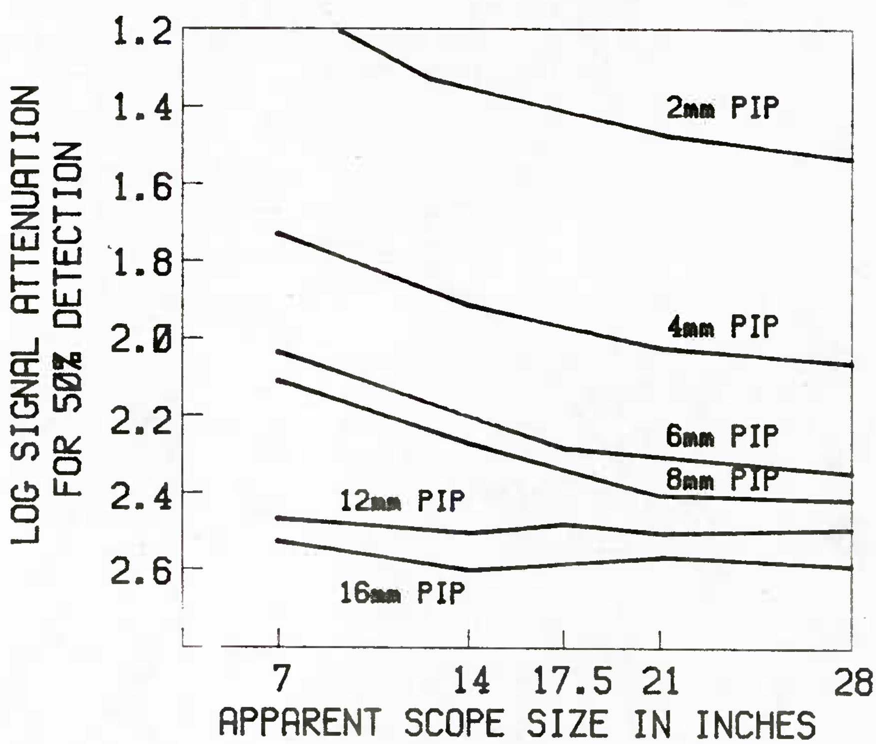


Figure 38. Signal requirements for 50 percent detection as a function of apparent scope size for all pip sizes (Williams et al., 1955).

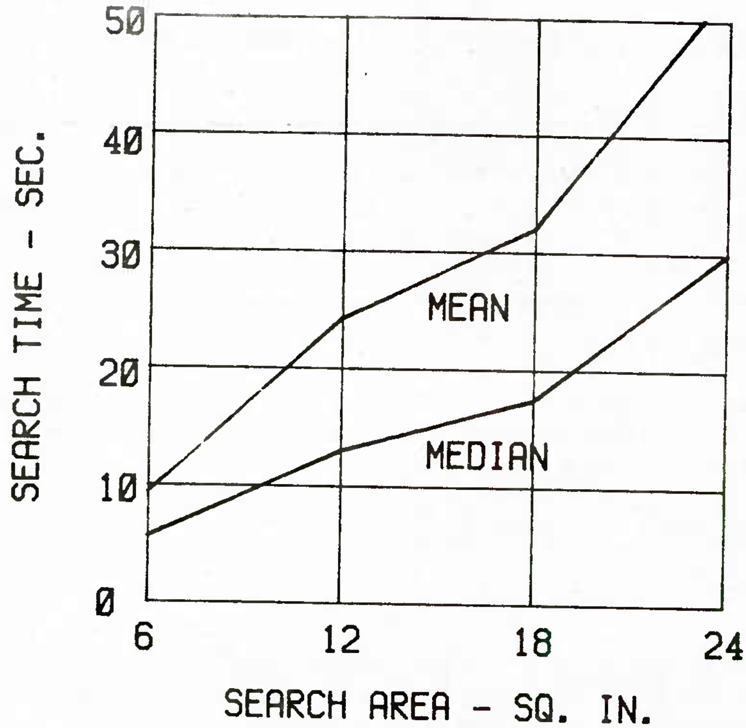


Figure 39. Search time vs. search area.

Figure 40 shows that the 7-inch scope is superior to the 10-inch; and the 10-inch, to the 14-inch at outer ranges (best for long range detection). Detection is degraded as search area is increased. Ranking is reversed at inner ranges (Baker, 1962). Additional evidence suggests that detection on a 6- to 9-inch display is superior to a 3-, 12-, and 14-inch display (see Figure 41) (Horowitz, 1965).

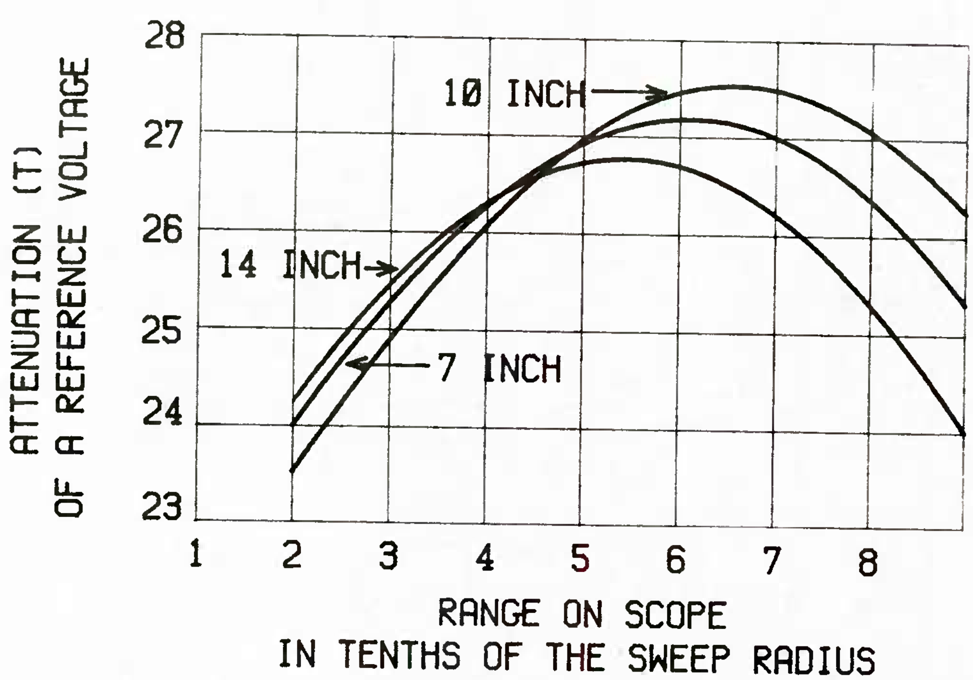


Figure 40. Target detectability as a function of range for three sizes of radar scopes (Baker, 1962).

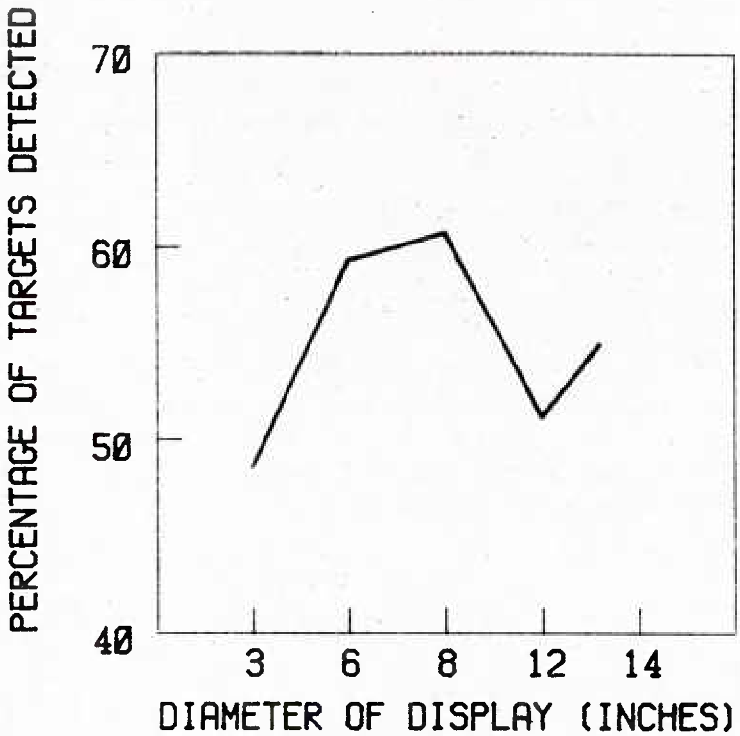


Figure 41. The percentage of targets detected on each of five sizes of displays (Baker & Earl, 1968).

The tradeoff is between pip size and scope size. Radar detection improves as pips get larger up to about 60 minutes of visual angle, but decreases continuously as the scope gets larger. The practical tradeoff suggests a scope size of 17.5 to 28 inches. Probably, the 7-inch scope would still be the best for different detection functions, but only if the pip could be enlarged without enlarging the scope.

As long as pip size is between 12 and 16 mm, the best scope size is in the range 12 to 16 inches diameter with the differences in this range being unimportant. The larger CRT scopes, which automatically magnify pip size, appear to be more effective for detection. There are also techniques for electronically amplifying pip size.

Pip detectability thresholds, usually expressed in terms of decibels attenuation of a reference voltage, can be predicted from display geometry using the regression equation below; adding regression terms for scope area and pip size does not improve the overall prediction.

$$Y = 7.02 + 3.33\,x - .22x^2 - .46\,xz + 2.09z \qquad (3.1)$$

where

- Y = mean detectability threshold in decibels attentuation of a reference voltage,
- x = target range in tenths of PPI radius,
- z = usable display diameter in units of 7 inches (Baker, 1962).

3.3 How Large Should the Pip Be?

Pip size is governed by a large number of factors that are ordinarily outside the control of the display designer. Primary among these factors are:

a. Pulse length.

b. Target extent (among the axis of the beam) in range.
c. Target extent in bearing.
d. Scan rate.
e. Echo level.
f. Signal-to-noise ratio.
g. Bandwidth.
h. Phosphor characteristics.
i. Resolution requirements.

Within the constraints imposed by these factors, Figure 42 suggests that the minimum target size for recognition is 12 minutes of arc. This assumes high contrast and ideal viewing conditions. To design operational equipment, a safer bet is that the minimum visual angle should be approximately 20 minutes.

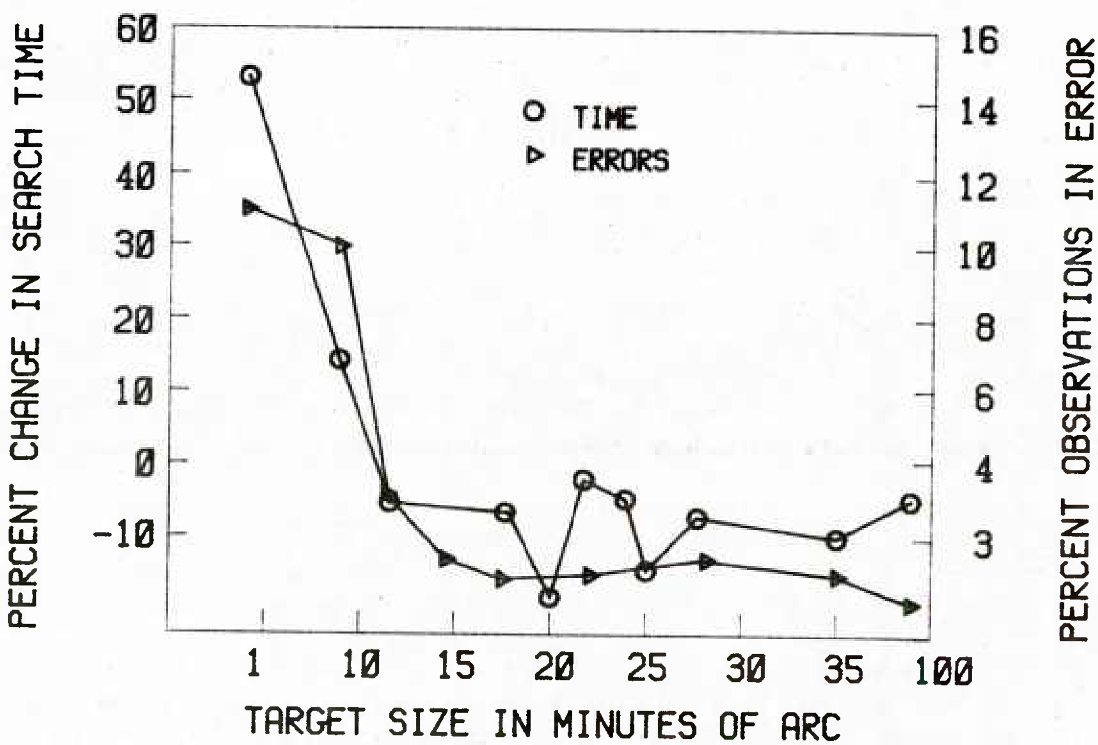


Figure 42. Relative increase or decrease in search time and errors as a function of target size (Steedman & Baker, 1960).

Within the ranges of 7 to 28 inches of scope diameter and 2 to 16 mm of pip diameter, the larger the pip, the less important is scope size. Medium and small scopes can be at least as efficient as large scopes at the same level of resolution (Colman, Courtney, Freeman, & Bernstein, 1958). The minimum usually detectable separation between targets is 1 minute of arc, which is beyond the capabilities of most present tubes.

Assuming that the angular subtense of the target image is 12 minutes of arc and the viewing distance from the image is 12 inches, the minimum displayed image size for relatively accurate and rapid recognition is .04 inches. With visual angle of 12 minutes and a viewing distance of 12 inches, the following can be used to plot display size against target size (see Figure 43):

$$\text{Display size (inches)} = \frac{\text{ground range}}{\text{target size}} \times .042. \tag{3.2}$$

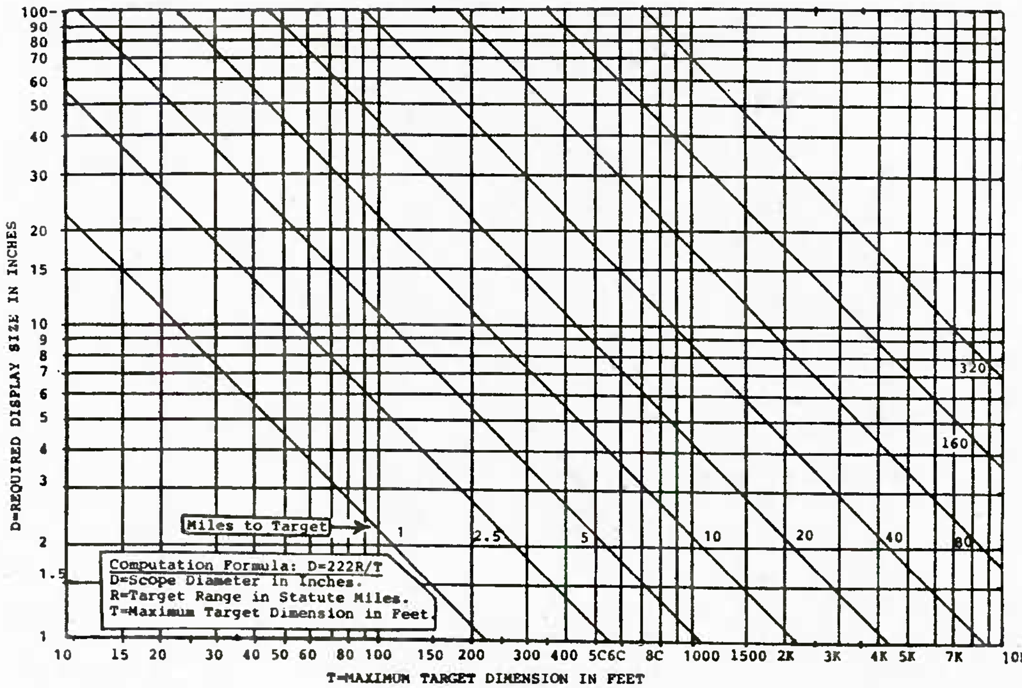


Figure 43. Required display size plotted against target size for various ground ranges displayed to the observer.

Example. If the smallest target needed for recognition is 1000 feet in its greatest dimension and the system displays (a target range) an analog of a strip of ground 40 miles wide, the display must have one dimension of not less than 10.2 inches (Steedman & Baker, 1960).

Detectability varies with the size of the signal. For signals from approximately 1 mm^2 to 2 cm^2, the slope of the size-detectability relationship is essentially linear (see Figure 44). Beyond signals of 2 cm^2, the slope levels off. This is true for both bright and dim background luminance (Deese, 1954).

3.4 How Persistent Should the Pip Be?

For the eye to detect the presence of a signal on a CRT, the signal must be bright and large enough or present for a long enough period of time. For detection of weak signals on a CRT, the signal must appear for a minimum of 0.1 second. Maximum visual sensitivity of the eye occurs between .2 and .3 second of observation time. Figure 45 indicates that for detection of relatively weak signals, .1 second is the minimum level of acceptable exposure time.

For every increase in unit log area visual angle of signals, detectability will increase about 8 dB. By doubling the area of a display and assuming resolution is constant, detectability increases about 2 dB for all but the very largest signals (Baker, 1963).

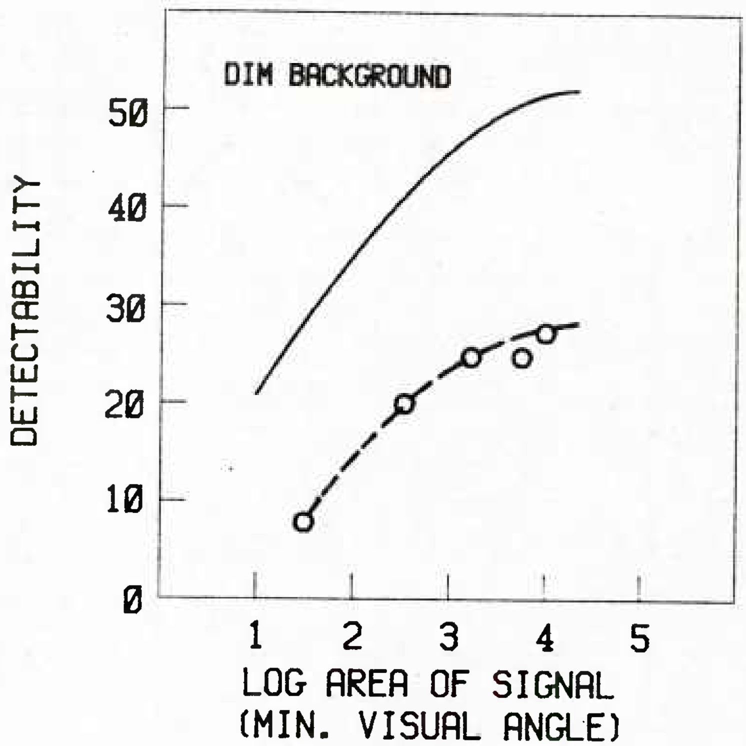


Figure 44. Detectability as a function of signal size for a CRT bias of 2 volts below visual reference index (VRI) (-22 volts). The background luminance is approximately 0.01 mL at 10 degrees behind the sweep. A similar curve is found for a CRT bias of 10 volts below VRI (-16 volts) (Deese, 1954).

Baker (1962) defines visual reference index as "a dim screen on which the sweep line is barely visible.

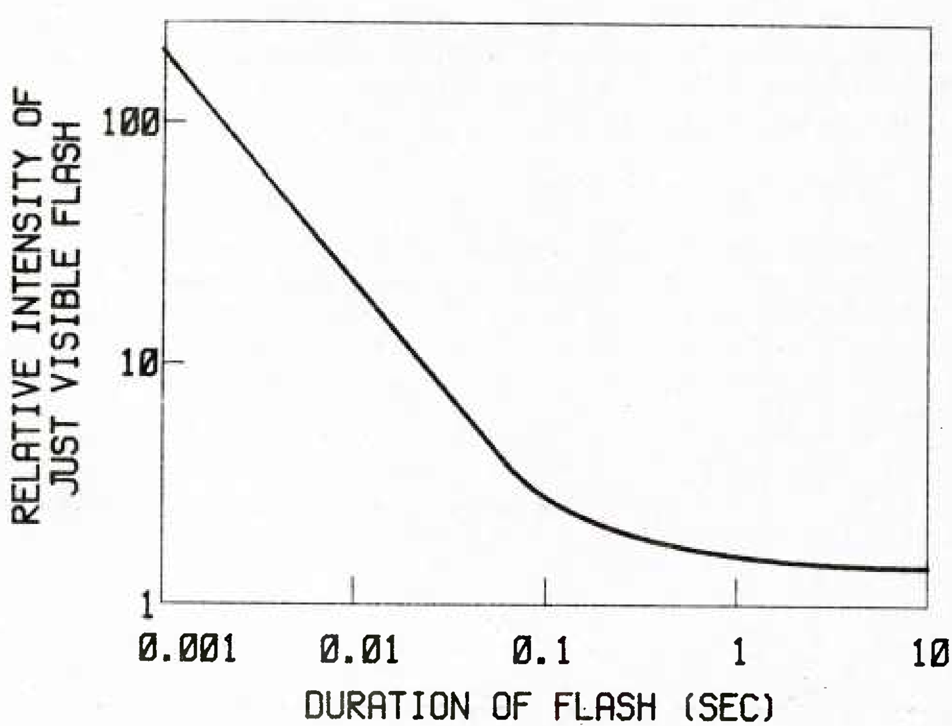


Figure 45. Signal persistance.

3.5 What is the Most Desirable Scanning Rate?

The PPI scanning rate for the optimal 7-inch tube in a radar application should not be less than 12 rpm, preferably higher (Kober, 1952). However, data on larger tubes are lacking.

3.6 What Should the Display Viewing Distance Be?

The following recommendations concerning display viewing distance have been made:

a. TUB--50 cm (20 inches).

b. DIN--50 to 70 cm (20 to 28 inches); 50 cm viewing distance is required if a keyboard or source document is used.

c. U of L--Regardless of whether obtained from manipulated viewing distance or optical correction, 2/3 or less of the full range of human accommodation will be used.

d. VDT--70 cm (28 inches) maximum.

e. SNBOSH--Adjustable.

f. MILSTD--410 mm (16 inches) whenever possible; 250 to 410 mm permissable.

g. Meister and Sullivan (1969)--For console viewing, 18 inches is recommended; viewing distances less than 16 inches are not recommended. In general, the maximum is 50 to 70 cm (19 to 27 inches). At greater distances, display size, symbol size, brightness, etc. should be modified, presumably in an increasing direction. Although this requirement does not directly impact on display design as long as the intended viewing distance is within the maxima indicated, if it is suspected that these maxima will be exceeded operationally, the designer should take the necessary steps.

3.7 What is the Most Desirable Viewing Angle?

Optimally, the most desirable viewing angle is at right angles (90 degrees) to the plane of the PPI screen. If necessary, viewing angles up to 30 degrees from the perpendicular can be tolerated, but with some loss of pip visibility. Between 0 and 30 degrees from the perpendicular, visibility is unimpaired. At 45 degrees, there is a drop of 3 dB and, at 60 degrees from the perpendicular, a further drop of 3 dB (Kober, 1952). For nonelectronic displays, research has shown that performance decrements begin to occur somewhere between 19 degrees and 38 degrees from the perpendicular.

3.8 Display Brightness

Scope brightness should be between 10 and 100 fL, depending on the type of display and ambient illumination. The ideal background scope brightness for high ambient illumination should be about 100 fL (Dyer & Christman, 1965).

The visibility of the radar pip increases with display brightness. Figure 17 shows that, as background brightness increases, the visual angle that can be resolved becomes smaller and smaller. Figures 46 and 47, which present data more specific to the CRT pip, indicate that the visiblity of the pip increases with brightness, as does the range at which it is detected (Baker, 1962).

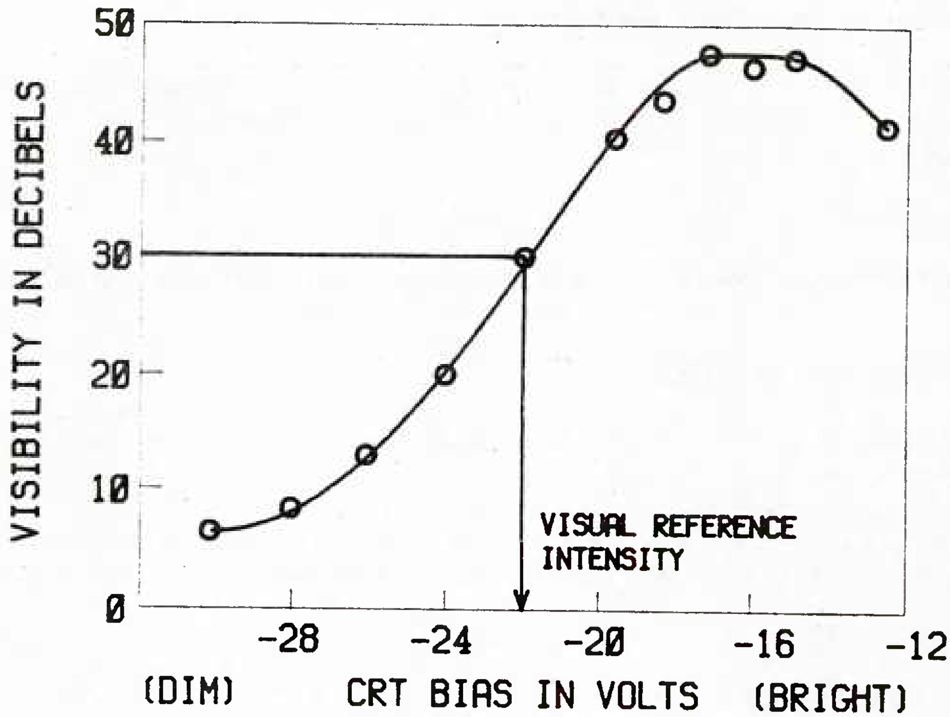


Figure 46. Pip visibility threshold and display brightness (CRT bias) on a PPI (Williams, 1949b).

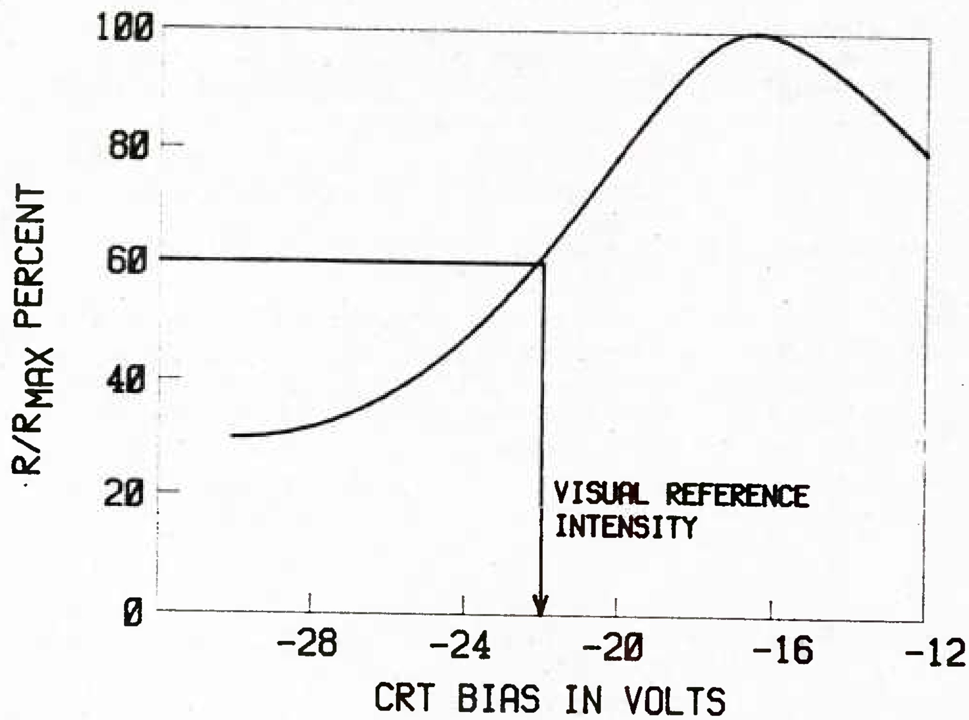


Figure 47. Percentage of maximum range at which a pip is visible as a function of display brightness (Thornton, 1954)

3.9 Pip Visibility: CRT Bias and Gain

The most effective pip visibility occurs with a low to moderate gain, as shown in Figure 48 (Baker, 1963). Optimum detectability (i.e., detection of weak pips) occurs at an intensity and bias in the middle range of values (Grant et al., 1961). Investigation of B-scan bias levels indicates that optimum bias level is independent of noise; however, detection is improved as noise increases (Gardner & Carl, 1959).

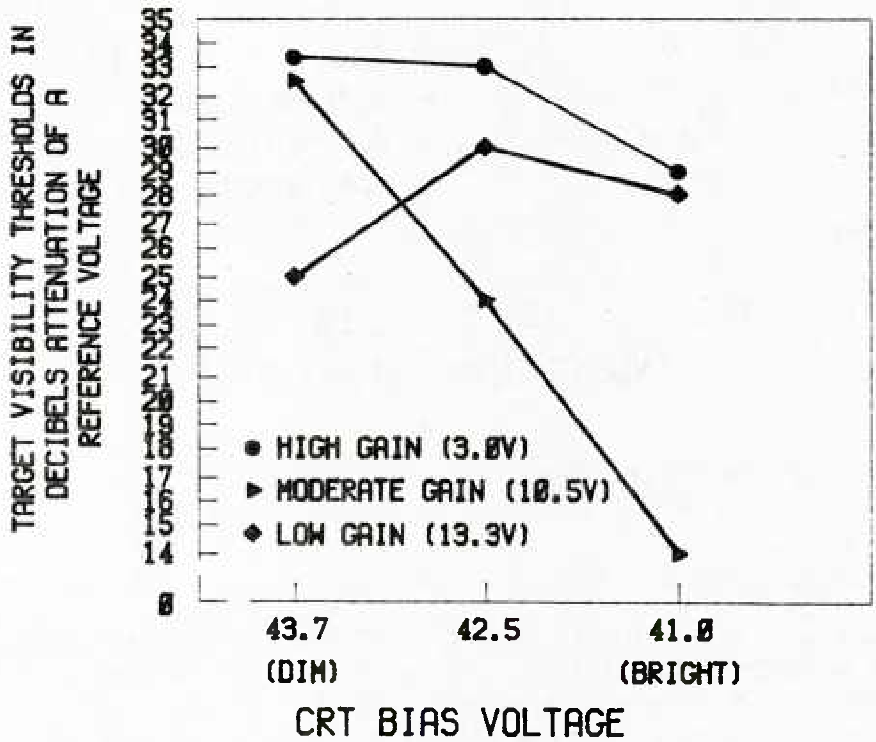


Figure 48. Target visibility thresholds and CRT bias for three levels of gain (Baker, 1963).

3.9.1 Considerations

In general, the higher the beam current is, the longer is the visual persistence of the strong signals. Maximum visibility of a signal during the first 7 seconds after excitation is obtained with a CRT bias in which the sweep is fairly dim, yet clearly detectable. For images having decayed more than 7 seconds, best visibility occurs at a high bias furnishing a less bright sweep. These effects are shown in Figure 49.

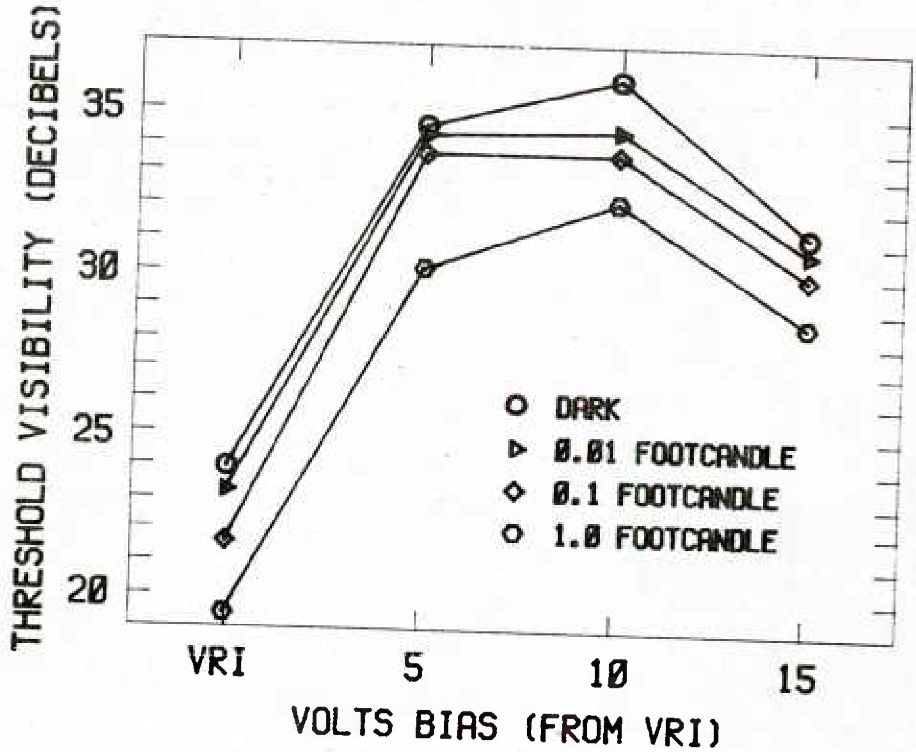


Figure 49. Target visibility as a function of CRT bias.

3.9.2 Brightness Adjustment

Operators are commonly allowed to adjust the brightness setting of their displays. There is evidence, however, that they cannot do this efficiently (see Figure 50). Analytically determined brightness adjustments give better pip visibility. A simple technique that is recommended is to use a light filter of such a density that making the sweep line just visible through it provides optimum brightness or noise level. Such a filter would be specific to a particular scope (Baker, 1963).

There is a gradient of scope brightness in the radial dimension on a PPI. Detectability threshold signal-to-noise (S/N) ratios are a function of radial range. Because of this, the setting of optimum brightness should be made with reference to the radial position that is of greatest importance in detection. In early warning radars, optimum brightness should be set near the periphery of the scope. Whenever radar range scales are changed, scope brightness changes and must be reset to restore optimum brightness. The grid voltage required to generate optimum brightness changes as the CRT ages; hence, brightness must be adjusted periodically (Baker, 1962).

Figure 51 shows that a reduction in any one factor--background luminance, symbol size, or contrast--may be compensated for by an increase in one or more of the others. As an example, the chief effect of reducing contrast is a shifting the curve up in the direction of increased target size for a given probability of detection.

Figure 52 shows that, with large targets on bright backgrounds (curves for 121 and 360 minutes of visual angle), the brightness contrast can be low and still provide a high probability of detection. (The curves in the figure are the contrast required for 50 percent detection probability.)

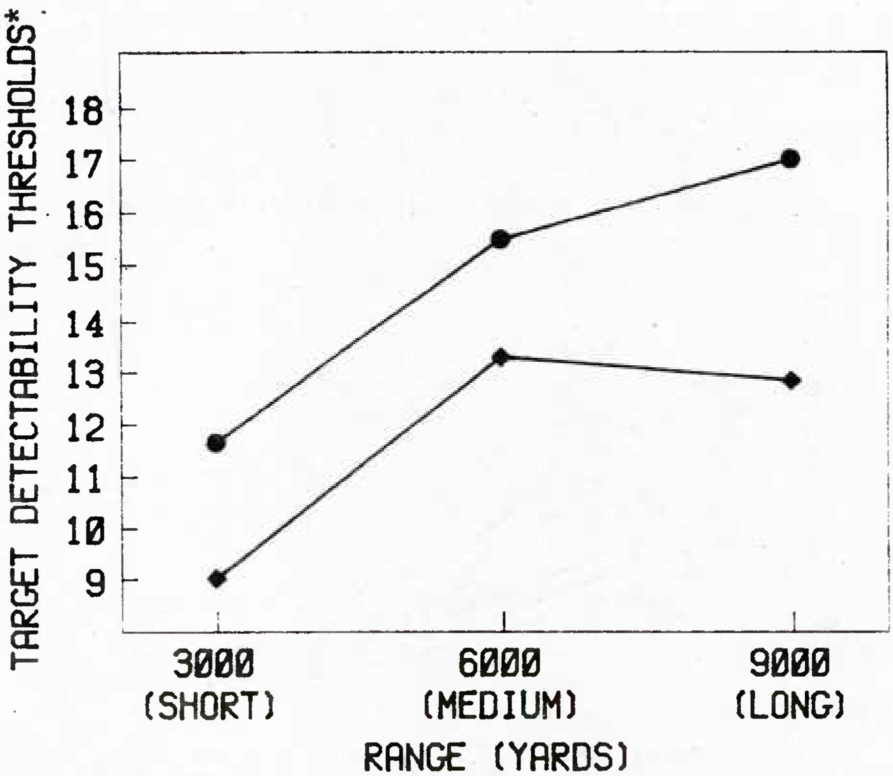


Figure 50. Comparison of target detectability thresholds.
*In decibels attentuation of a reference voltage.

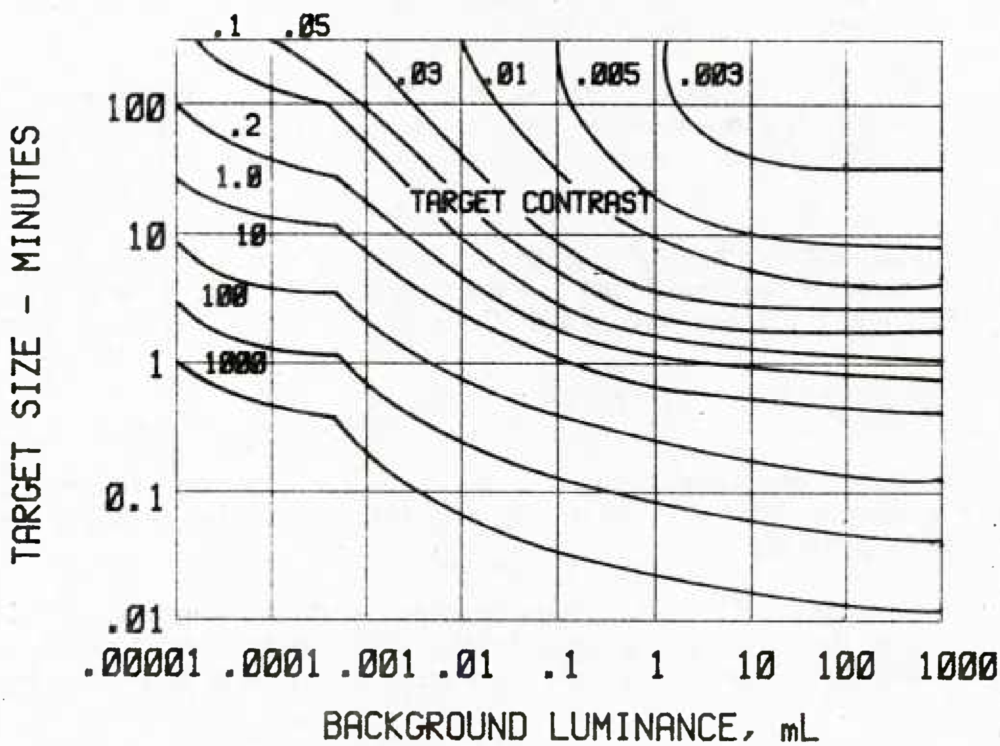


Figure 51. Relation between target size, threshold background luminance, and contrast (Lovelace Foundation, 1968) (Stimuli are uniform discs on a uniform background).

Note. Thresholds are at the 50 percent probability of detection; multiplying the values by 2 (log .3), the values can be converted to about the 95 percent probability of detection.

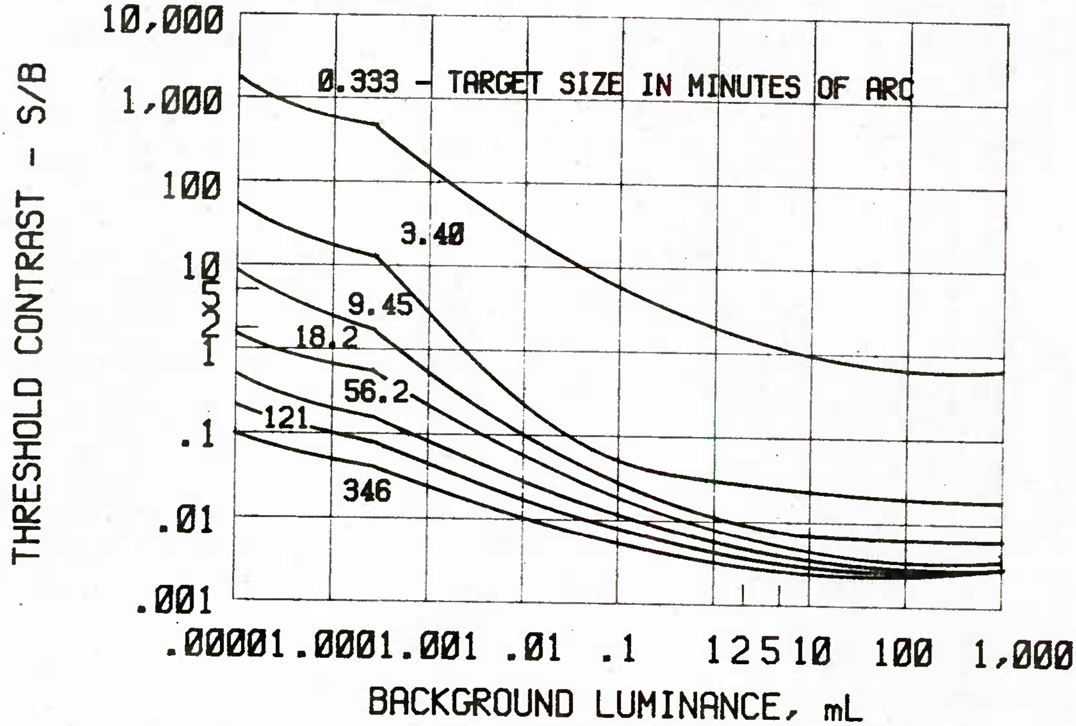


Figure 52. Contrast thresholds for different target sizes and background luminance (Lovelace Foundation, 1968).

Note. Thresholds are at the 50 percent probability of detection; multiplying the values by 2 (log .3), the values can be converted to about the 95 percent probability of detection.

Contrast enhancement by edge sharpening techniques that tend to increase both resolution and contrast has been found to increase probabilities of detection, recognition, and designation and the speed with which these events occur (Humes & Bauerschmidt, 1968).

3.10 Noise Effects

The effect of Gaussian noise on pip visibility is shown in Figure 53. Noise reduces the amount of improvement found in operating at optimum brightness, but the improvement still persists.

As expected, CRT detection is degraded with an increase in display noise. Figure 54 indicates that, at optimum scope brightness, noise impairs visibility, but, with a dim scope, it actually aids visibility, since the noise adds needed brightness to the scope (Baker, 1962).

Detection and localization performance as a function of S/N ratio and ambient illumination for several common phosphors is shown in Figure 55 (Sonn & Carr, 1967). The curves presented show a strong dependance of detection probability on S/N ratio.

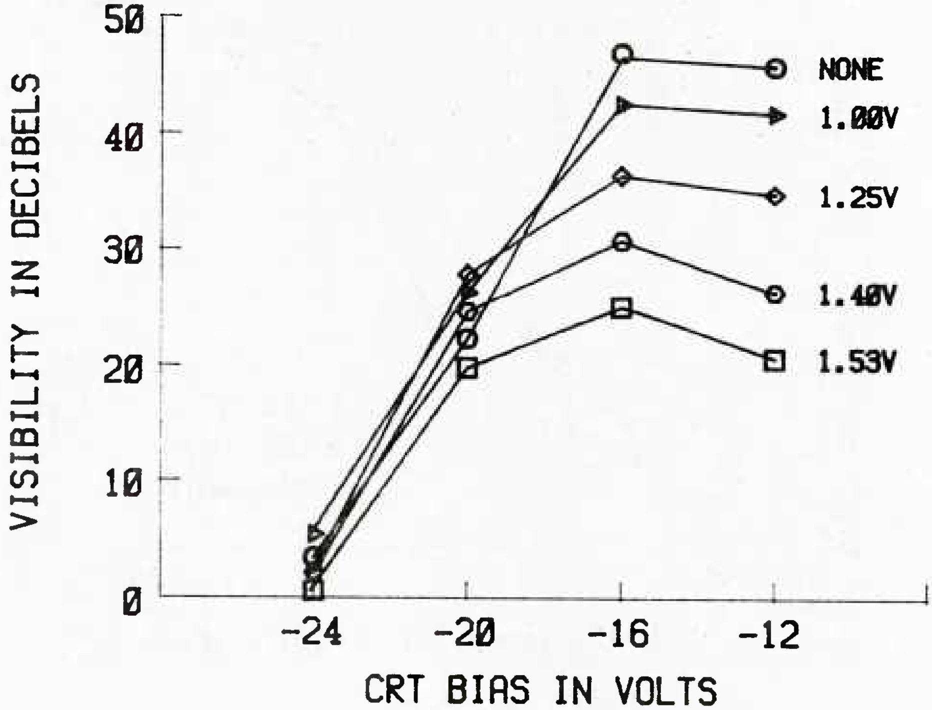


Figure 53. Effect of noise on pip visibility (Williams, 1949b).

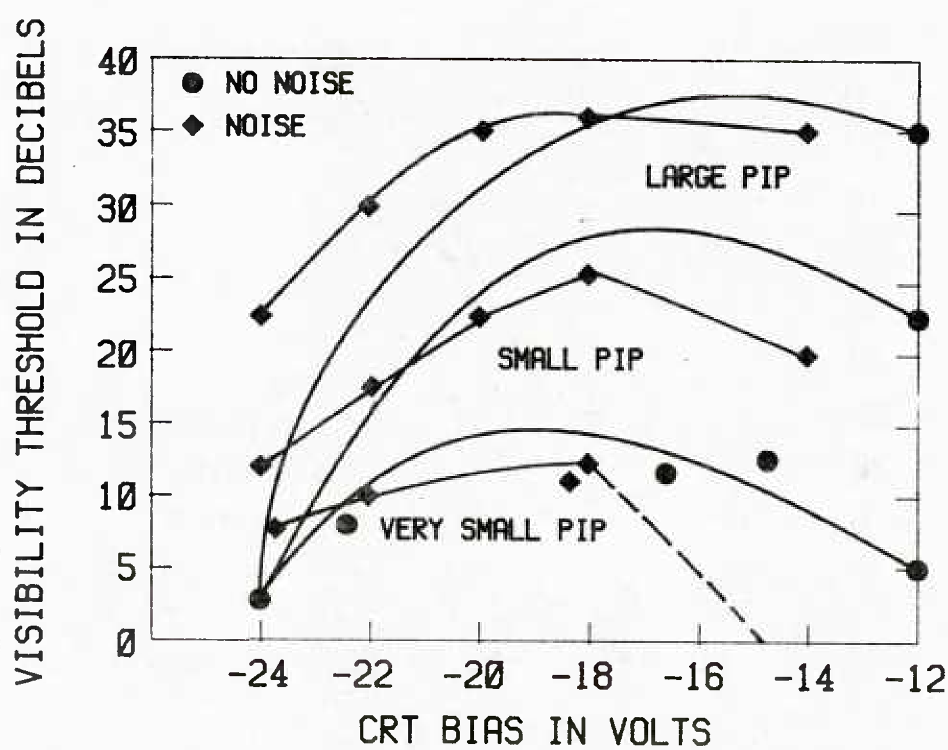


Figure 54. Pip visibility threshold and scope brightness for pips of three sizes under noise and noise-free conditions.

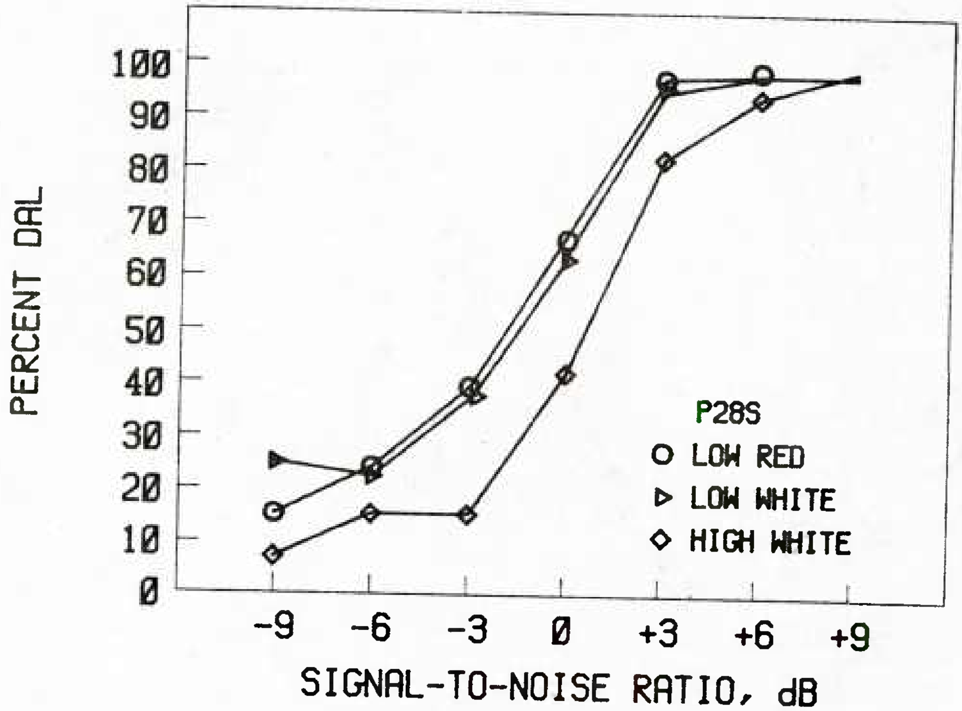


Figure 55a. P28S.

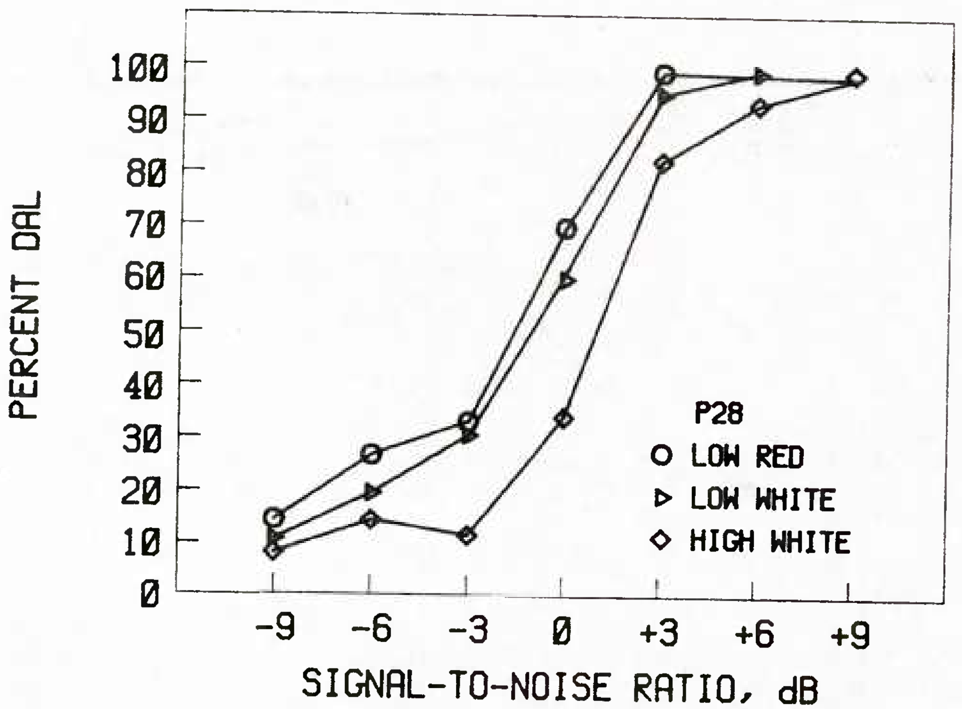


Figure 55b. P28.

Figure 55. Detection-and-localization (DAL) accuracy as a function of signal-to-noise ratio with ambient lighting as the parameter.

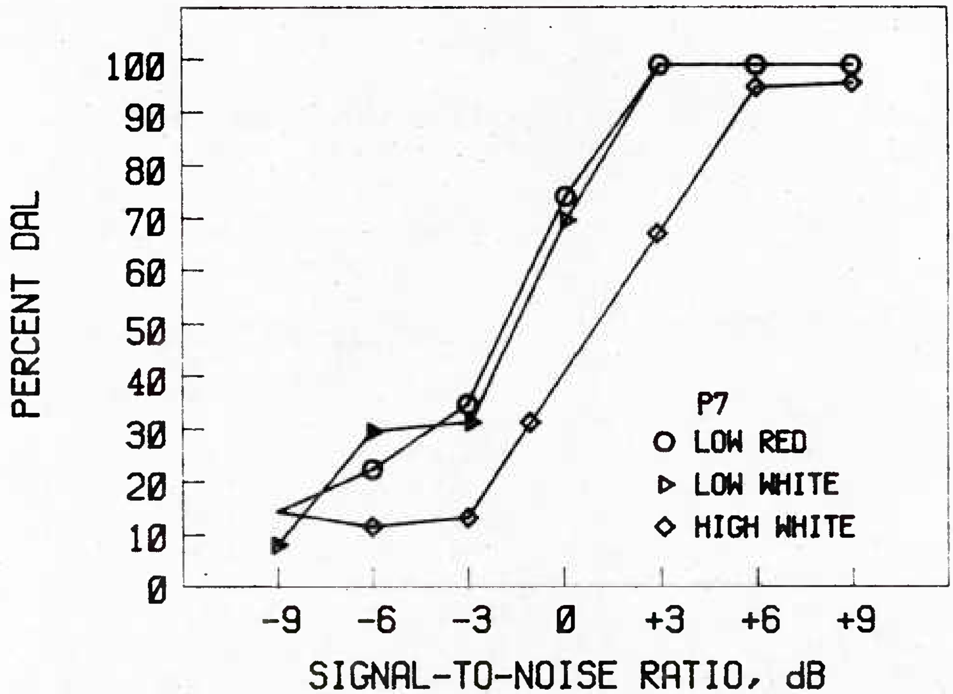


Figure 55c. P7.

The studies in this area generally demonstrate the following (Snyder, 1980):

a. Improvement in performance or in subjective image quality results from increases in S/N up to about 35 dB.

b. Noise spatial frequencies in the range of target spatial frequencies have the greatest masking effect on the target.

c. Lower spatial frequency noise is generally more harmful than higher spatial frequency noise, if noise power is kept constant.

d. Targets can be detected at very low S/N levels, on the order of 2.5.

e. Difficult tasks are most sensitive to noise than are easier tasks. (p. 296)

3.11 Target Symbols

The ability to identify (as opposed to detecting) different target shapes on a PPI scope varies as a function of the shape used. Table 14 shows accuracy of identification of common geometric shapes under conditions of low and high noise (Baker, 1962).

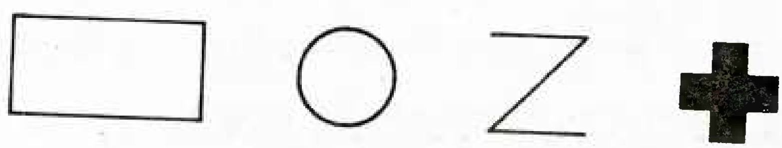
At viewing distances up to 10 feet, symbols should be .4 inch or larger (i.e., fit into a .4 x .4 inch square. Stroke width to height ratios should be between 1:6 and 1:10. The symbols should subtend at least 22 minutes of arc at the observer's eye (Baker, 1962).

Table 14

Accuracy of Identification of Geometric Shapes Under Low/High Noise Conditions

Target Shape	Percent Correct Identification	
	Low Noise	High Noise
Triangle	88 (1)	56 (1)
Square	29 (4)	35 (2)
Circle	76 (2)	27 (3)
Cross	-----	22 (4)
Trapezoid	70 (3)	-----
Rectangle	37 (5)	-----
Ellipse	30 (6)	-----

Another study showed that the four following symbols are most legible:



3.12 <u>Ambient Illumination</u>

Ambient illumination levels up .1 fc do not impair pip visibility, but higher levels impair detectability (Adler et al., 1953) (see also Figures 56 and 57). This applies regardless of the color (e.g., red) of the ambient lighting.

Scope brightness should be adjusted so that the higher levels of illumination that must be tolerated are not more than 100 times the average scope brightness. Except for radar used in aircraft, the brightness levels of the scope and the physical surroundings should be similar, which is often difficult to accomplish.

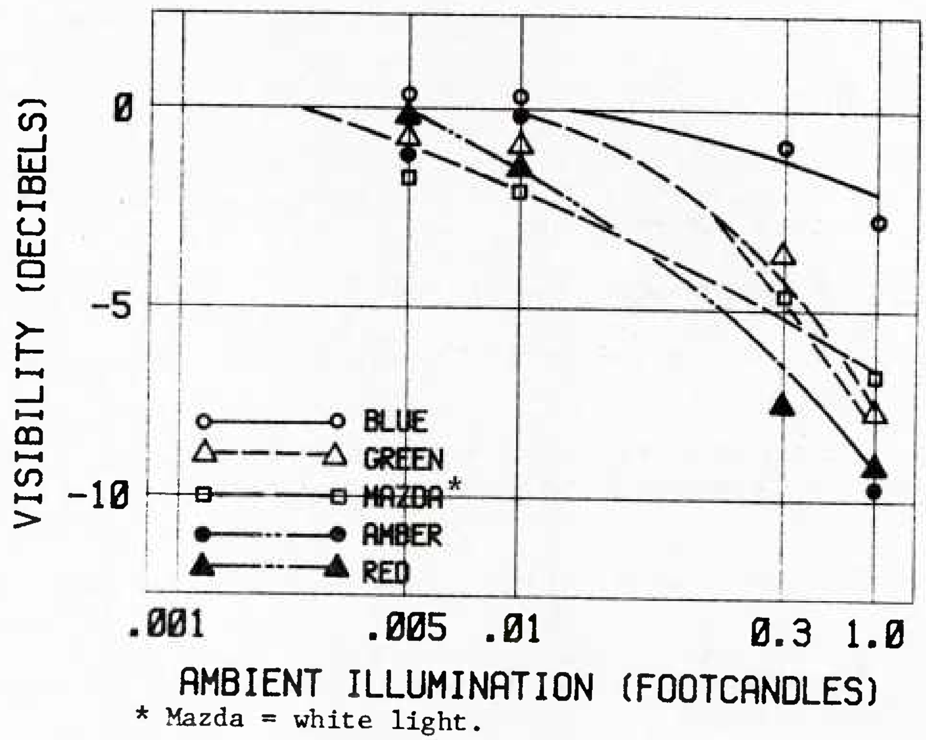


Figure 56. Visibility and ambient illumination (Baker, 1960).

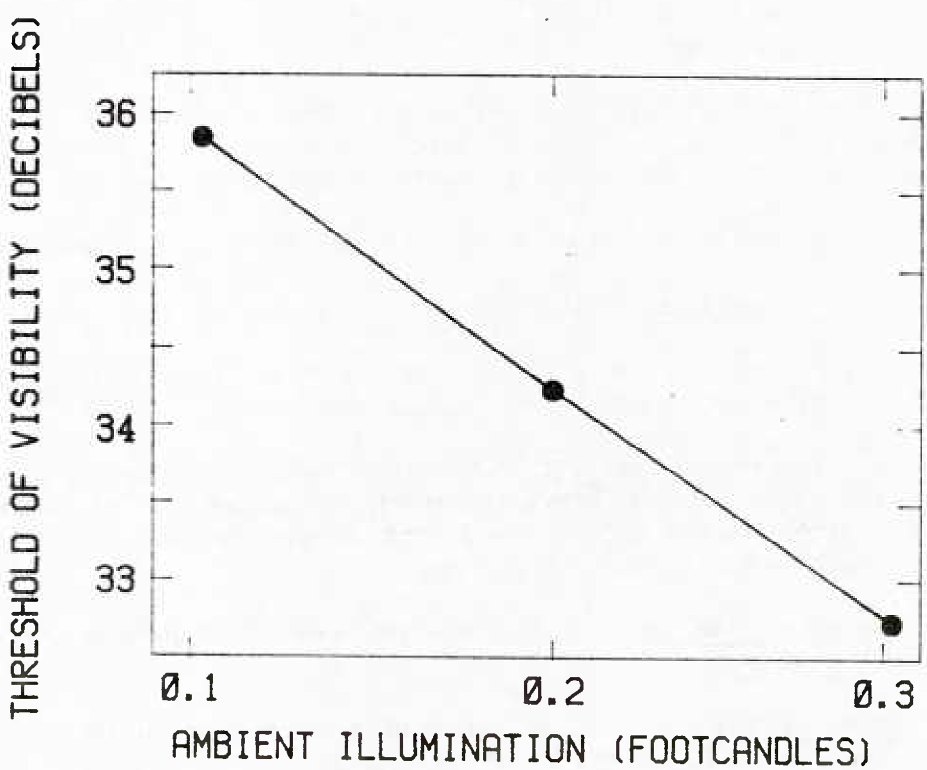


Figure 57. Decrease in target visibility at higher light levels (Baker, 1960).

3.13 Phosphors

Tables 15 and 16 present information on the characteristics of phosphors available for display applications (Gould, 1968; Luxenberg & Kuehn, 1968; updated by reference to Woodson & Coburn, 1980).

3.14 Operator Performance Characteristics

a. There are large individual differences among operators in detecting targets on PPI displays.

b. The requirement to search the entire PPI scope results in about 13 percent fewer detections on the average than when the operator is alerted to the target's probable bearing.

c. Detection of targets at midrange on the PPI is more rapid than at close or far range.

d. Repeated presentations of a target (up to 5 echoes) are often necessary to elicit valid detection reports.

e. The range between 10 and 90 percent probability of detection on a PPI is only about 4.5 dB.

f. Setting the PPI scope brightness at the visual reference intensity (VRI), as often recommended, adversely affects target detection. The optimum brightness for detection is well above this setting.

g. Operators typically do not adjust CRT bias and gain optimally for detection. Weak signals can be detected much more frequently using experimentally determined optimum settings than when the operator uses his own setting.

h. Signals can be missed even when the eyes are fixated on the PPI.

3.15 Equipment Considerations

a. Pulse length. Increasing pulse length of short pulses improves detection very markedly; the effect on longer pulses is not as significant.

b. Antenna rotation rate. If the rotation rate is sufficient to paint a uniform background on the scope, detectability is essentially independent of rotation rate. If the background is discontinuous and "grainy," the slower rotation rates are slightly advantageous, over a range of about 1 to 70 rpm.

c. Sweep rotation rate. The slower the sweep rotation rate, the higher is the detectability of the signal.

d. Beam width. The beam width of the antenna largely determines the angular dimension of the pip. From 2 to 12 degrees, detection improves as the 2/3 power of beam width.

e. Video band width. No effect of video band width on detection has been found.

Table 15

Characteristics of Available Phosphors

Phosphor No.	Persistence[b]	Color[a] Fluorescence	Phosphorescence	CIE Coordin. x	y	Spectral Range (Angstroms)	Decay Time (msec)	Uses	Note[c]
P1	M	YG	YG	.218	.712	4750-6600	24	Radar, sonar, oscilloscopes.	High resistance to burn, high efficiency, high apparent resolution.
P2	M	YG	YG	.279	.534	4200-6200	35-100	Radar, sonar, oscilloscopes.	Decay decreases as beam current increases.
P3	M	YG	YO	—	—	—	--	---	---
P4	M/MS	W	W	.270	.300	3900-7000	25	Monochrome TV.	Sulfide version of P4; there are two others referred to as sulfide-silicate and all-silicate.
P5	MS	B	B	.169	.132	3300-7000	25	Photography.	—
P6	—	--	--	—	--	--	--	Obsolete.	---
P7	L	Y	YG	—	—	4000-7000	—	Radar, sonar, ocsilloscopes.	High efficiency, high resistance to burn. Amber filter must be used to obtain long persistence.
	MS	B	B	--	--	4000-4700	—	Radar, sonar, oscilloscopes.	
	--	W	YG	.151	.032	4000-6100	40-60	---	
P8 P9 P10	—	--	—	—	—	--	—	Obsolete.	—
P11	L	B	B	.139	.148	4000-5450	25-80	Photography.	May contain nickel to decrease persistence.
P12	MS	O	O	.605	.394	5250-7000	—	Radar	—
P14	M	YO	O	.504	.443	5000-7000	—	Military displays where repetition	—
	MS	B	O	.150	.093	4000-4700	—	rate is 2-4 sec. after excitation	—
	MS	PB	YO	—	—	4000-6600	--	is removed.	---
P15	VS	G	G	—	—	3600-6600	—	TV pickup of photographs by flying spot scanning.	---
P16	VS	BP	BP	.175	.003	3350-5100	0.12	TV pickup of photographs by flying spot scanning.	—
P17	L	B	Y	.302	.390	4000-7000	—	Military displays.	—
	VS	G	BP	—	—	3600-6600	—	---	—
	S	YW, BW	Y	—	—	3600-6600	—	---	—
P18	M	W	W	.333	.347	—	—	Low frame-rate TV.	---
P19	L	O	O	.572	.422	5400-7000	—	Radar indicators.	Slow refresh rate for flickerless display. Low light output, low resistance to burn.
P20	M/MS	YG	YG	.444	.536	4500-7500	.01-2	High visibility displays.	A range of CIE coordinates and, hence, colors are permitted. Coordinates states are for a representative P20 employed in preparation of P4.
P21	M	RO	RO	.539	.373	4000-7000	—	Radar.	---
P22	M	B	B	.155	.060	5600-7400	25	Color TV.	Data for sulfide blue and green, and vanadate red.
	M	YG	YG	.285	.600	4700-6200	60	Color TV.	—
	M	OR	OR	.675	.325	5600-7400	0.9	Color TV.	—
P23	M	G	G	—	—	4700-6200	—	Interchangeable with P4.	—
	MS	B	B	—	—	3800-5700	—	---	—
	M	W	W	—	—	4200-7000	—	---	—
P24	S	G	G	—	—	3950-7150	—	Flying spot scanner tubes.	---
P25	M	O	O	.557	.430	5400-6950	45	Long persistence displays up to 10 seconds.	Desired low-level persistence, high resistance to burn. Low light output.
P26	VL	O	O	.582	.416	5400-6800	—	Radar displays.	Slow refresh rate for flickerless display. Low light output, low resistance to burn.
P27	M	RO	RO	.674	.326	5925-7000	27	Color TV monitors.	---
P28	L	YG	YG	.370	.540	4625-6300	.5 sec	Radar and sonar.	Curve has shoulder on long wavelength side at 580 nanometers.
P29	M	G	G	$(P_2 + P_{25})$	—	—	—	Aircraft indicators, radar.	---
P31	MS	G	G	.193	.420	4100-6500	4	Oscilloscopes.	Curve also has blue peak at 450 nanometers. High efficiency, high resistance to burn, high apparent resolution.
P32	L	PB	YG	—	—	4000-6300		Radar.	---
P33	VL	O	O	.559	.440	5500-6550	—	Radar.	Decay decreases as beam current decreases, burning very rapidly when used with stationary or slow-moving electron beam.
P34	VL	BG	YG	.235	.364	5100-6300	40 sec	Oscilloscopes, radar.	Infrared stimulable phosphor, Y-phosphor.
P35	MS	G	B	.286	.420	4200-6700	1	Oscilloscopes.	Resists burning compared to P11.
P36	VS	YG	YG	.400	.543	4700-6700	25	Flying spot scanning tubes.	Similar to P20, but with shorter decay.
P37	VS	B	B	.143	.208	4000-5500	.155	Flying spot scanning tubes.	Similar to P11, but with shorter decay.
P38	VL	O	O	.561	.437	5300-6800	1040	Integrating phosphor for low repetition rate displays and radar.	—
P39	L	YG	YG	.223	.698	4800-5700	150	Integrating phosphor for low repetition rate displays and radar.	Similar to P1, but with longer decay.
P40	M	WB	YG	.276	.3117	4000-6000	—	Integrating phosphor for low repetition rate displays and radar.	Similar to P7, but with longer decay.

[a]Color Code:

P = Purple O = Orange
B = Blue R = Red
G = Green W = White
Y = Yellow

[b]Persistance Code:

VL = Very long = 1 sec or more
L = Long = 100 msec to 1 sec
M = Medium = 1 msec to 100 msec
MS = Medium short = 10 μsec to 1 msec
S = Short = 1 μsec to 10 μsec
VS = Very short = less than 1 μsec

[c]From Luxenberg and Keuhn, 1968.

Table 16

Persistence Characteristics and Critical Flicker Frequency (CFF) of Phosphors Commonly Used on Displays

Phosphor	% Residual Light after		Persistance to 10% (sec)	Empirically Determined CFF for Ambient Illumination Levels					
	1/30 sec	1/60 sec		10 fL	32 fL	50 fL	100 fL	10 mL	50 ml
P28	85	90	550×10^{-3}	34	40	31.4	46	--	--
P19	80	90	220×10^{-3}	--	--	17.5	--	--	--
P12	70	85	210×10^{-3}	25	29	--	32	--	--
P7 (Y)	45	80	400×10^{-3}	32	38	29.8 (B&Y)	43	--	--
P1	4	23	24.5×10^{-3}	33	38	29.2	43	32	38
P4 (y) Silicate	1.3	7	60×10^{-6}	35	41	33.5 (B&Y)	47	36	43
P31	1	1	38×10^{-6}	37	44	32.4	51	--	--
P20	1	1	50×10^{-6} to 18×10^{-3}	40	47	32.7	54	--	--

Note. From Gould, 1968.

f. Sweep direction. No significant difference between clockwise and counter-clockwise direction of movement of the sweep line.

g. Video gain. The higher the video gain, up to maximum, the easier it is to detect the target (lowered detectability threshold) within a device's dynamic range.

h. Interaction between gain and CRT bias. A more positive bias can help compensate for low gain and a high gain can help compensate for low bias.

i. Pulse repetition frequency (PRF). This is a measure of the frequency with which the electron beam excites the CRT phosphor. The probability of detection increases with increases in PRF.

3.16 Recommendations for CRT-PPI Displays (From Woodson & Coburn, 1980)

a. General requirements. The following are applicable to CRT selection and design regardless of specific use.

(1) Screen luminance. The screen luminance should be within a range that satisfies all the following requirements.

(2) Operating range. The luminance used should be compatible with the CRT's operating characteristics and life expectancy. That is, for example, the CRT should not be driven beyond its normal value in order to gain greater screen luminance since this could result in burning of the screen or in reduced life.

(3) Ambient illumination. CRT luminance should be compatible with the ambient illumination otherwise required in the work area, except that shielding, filtering or use of a hood may allow lower CRT luminance if the technique employed is compatible with the operator's task.

(4) Operator visual capabilities and task requirements. Luminance of the faintest information displayed for operator response should be well above the operator's threshold considering target size and presentation rate, clutter, phosphor color, and ambient illumination conditions.

b. Finish and luminance of surrounding area. Panel surfaces adjacent to the CRT should have a dull matte finish that, under ambient operational conditions, should have a luminance range between 10 and 100 percent of the screen background luminance. Some means of adjusting the surround luminance should be provided if necessary to ensure operation within this range.

c. Daylight viewing. CRTs that must be viewed under daylight conditions such as on the bridge of a ship or in an aircraft cockpit should utilize one or more appropriate means such as the following to bring viewing conditions within an acceptable range: (1) a deep shield or hood to reduce the amount of incident light, (2) scan conversion for continuous presentation at high luminance levels, (3) a high-output burn-resistant phosphor such as the P1 compatible with the higher ambient light levels, (4) a circularly polarized filter for cancellation of light reflected off the faceplate, (5) negative image polarity to present dark traces on a light background, (6) a filter/phosphor combination that will minimize screen fluorescence, and (7) a fiber-optic or mesh type filter that tends to reject incident light and pass screen-emitted light.

d. Reflection and glare. Reflection and glare off CRT faceplates and cover plates should be minimized by one or more appropriate techniques such as: (1) shielding the CRT or the light sources to prevent direct illumination from striking the CRT, (2) positioning light sources so they do not reflect off the CRT faceplate into the operator's eyes, (3) using a circularly polarized filter for cancellation of light reflected off the CRT faceplate, (4) using a cross-polarized lighting system (a polarizing filter over the CRT rotated 90 degrees with respect to polarizing filters over the light sources), (5) using a controlled white light system that delivers light only to the necessary work areas and baffles it from the CRT, (6) using a selective spectrum lighting system wherein the spectral output of the CRT is substantially outside the spectrum of the ambient illumination, and (7) applying an antireflective coating on the CRT faceplate and nonbonded filter surfaces to reduce the proportion of reflected light.

e. Use of color. Color is inherently a good coding dimension, but it should be utilized only when: (1) any loss of CRT resolution resulting from the use of color is acceptable, (2) color codes are compatible with color stereotypes and conventional usage, and (3) all users will be able to perceive the code. (Because there are some color deficient personnel in the armed forces, it cannot be assumed that any random operator will be able to differentiate the color codes reliably. Use of some other code redundantly along with the color code is the best way to ensure that the codes will be differentiable by all personnel. Thus, if friendly and hostile tracks are to be differentiated by color, they should also be differentiable by some other means such as shape coding.)

f. Persistence. Transient signals of very short duration such as those derived from radar and active sonar systems should be displayed with sufficient persistence for the operator to perform whatever operations are needed with respect to the signals. Persistence beyond signal duration on the display may be accomplished through use of persistent phosphors, periodic repainting (refreshing) of the image from processor memory, or utilization of scan converters or direct view storage tubes as appropriate to the application. With rotating sweep indicators, the persistence should at least be sufficient to display faint signals above threshold for a period equal to one-quarter of a sweep rotation. Short to medium persistence is adequate for scan rates such as those used for television.

g. Dynamic range. A dynamic range of at least 7 dB should be provided for detection of targets on a PPI, and 20 dB or more is desirable for detection on an A-scan presentation or other deflection display. A dynamic range of at least 7 dB should be provided for TV images, and applications where fine-grain detail is important, such as high-resolution reconnaisance sensors should provide the maximum attainable with the state of the art.

h. Jitter. Erratic movement of sweep traces on CRT displays should be diminished to the point where it is not detectable by the operator.

i. Flicker. The refresh (repaint) rate of signals or data displays on a CRT should not be between the rates of 7 and 28 Hz except in applications requiring sensor scanning at these rates. Rates between 1 and 7 Hz should be utilized only when it is desired to capitalize on the conspicuity value of such rates, such as for warning signals or in the rare circumstances when flash rate coding might be utilized. Refresh rates for data that are to be perceived continuously as presented should be increased from 28 Hz as necessary to reduce flicker to a nondetectable level over the entire range of display luminance.

j. Spot size and resolution. The spot size (diameter to 10% luminance) on a CRT should be compatible with the signal characteristics and type of scan to be utilized. For radar, the spot size preferably should be smaller than the minimum size of a returned pulse as presented on the slowest sweep (longest range scale) in order to avoid loss of resolving power inherent in the radar system. For most CRT display applications, spot diameter at all parts of the screen should subtend no more than 1 minute of arc from the normal viewing position. Alphanumeric characters should be scaled to subtend at least 15 minutes of arc; other complex shapes should subtend at least 20 minutes of arc.

k. Hand capacitance effects. For applications in which the operator's hand normally comes close to the screen, such as in plotting on the faceplate or using a light pencil for data pickoff, aluminized backing of the screen should be utilized to minimize the effect of hand capacitance that tends to add uncontrolled deflection to the CRT beam.

l. Burning of screen. The display design should minimize the likelihood of burning of long persistence phosphor screens such as the P19, P25, and P33, since it cannot be assumed that burn-damaged CRTs will always be properly replaced under operational conditions and the presence of burned areas seriously degrades display legibility. (Anti-burn techniques include use of aluminized backings and protective ciruits for automatic intensity reduction whenever the beam remains stationary.)

m. Distortion. Sweep nonlinearity with raster on PPI-type scans should be less than 2 percent. CRTs displaying only alphanumeric or graphics data should show no obvious distortion in any column or row of characters, and the character aspect ratio should appear to be constant at all parts of the screen.

n. Screen shape. CRT display surfaces used exclusively for data presentation or computer graphics should be rectangular in shape. CRT displays used exclusively for TV image presentation should also be rectangular and should normally follow the standard practice of having a 3:4 aspect ratio (height to width). Those CRTs used exclusively for polar plots of sensor data should be round. The preferred display surface shape for A-scan presentations is rectangular. CRTs used simultaneously or sequentially for two or more different display functions may have round, square, or rectangular display surfaces as best fit the combined purposes.

o. Useful screen diameter. The diameter of direct-viewing console-mounted CRTs should normally be within the following limits. (CRTs smaller than those listed for detection, detection and tracking, and situation display may be used where there are severe space constraints such as in aircraft or submarines or hand-held units.)

(1) For detection of signals from sensor systems--21.5 cm (8.5 inches) ± 3 1/2 cm (1.5 inches).

(2) For both detection and tracking--30 cm (12 inches) ± 5 cm (2 inches).

(3) Tactical or situation displays--At least 38 cm (15 inches), maximum 76 cm (30 inches).

(4) Alphanumeric displays--Size these by considering the largest format that will be required and the recommended character size.

(5) TV--Minimum 12 cm (5 inches), maximum 60 cm (24 inches).

(6) Single character display--1.9 cm (.75 inch) minimum.

(7) Display of single pulse or short sweep segment for qualitative monitoring only--1.9 cm (.75 inch) minimum.

p. Viewer protection. A transparent safety screen that is integral with the CRT faceplace should be provided to prevent implosion injury. Protection as needed should also be provided against low-intensity X-radiation as prescribed by current regulations of the Bureau of Radiological Health of the Food and Drug Administration.

q. Display composition features. Convenient controls should be provided for structuring the display format and content in accordance with user requirements. Display capability should be provided to present both the current setting of all controls relating to display composition, and the total range of settings available.

r. Viewing angle. CRT screens should be perpendicular to the operator's line of sight (i.e., have a 90 degrees viewing angle at screen center) whenever feasible and no part of any screen including secondary CRTs should offer a viewing angle of more than 45 degrees from the perpendicular.

3.17 Factors Affecting Radar Operator Efficiency

The following material is excerpted from a compilation of research that Baker and Thornton published some years ago (1957). Although the internal technology of the CRT systems has changed substantially over the years, the PPI presentation has not. Since the display of raw video is being discussed, the data are not relevant to displays whose output has already been processed by a computer. The operator's response described here is to a "pip" defined as a visually appreciated change in phosphor brightness. Source and source conditions (where available) are noted.

a. Pip brightness (P7 phosphor) on successive sweeps. With the second sweep, there is a small but significant increase of pip visibility (1 to 2 dB over signal voltage) over the first. This is further enhanced on the third scan.

b. Pip detectability. Detectability increases with video gain. For each video gain, there is an optimum CRT bias. There is an interaction between CRT bias and video gain that affects detectability. A less negative CRT bias can partially compensate for a low video gain and a high gain can partially compensate for a very negative bias. If bias is decreased, detectability is increased within limits. Video gain has much less effect on detectability when the CRT is less negative. There is a "best" video gain and a "best" CRT bias for that gain. The optimum CRT bias for one system is different from that of another system.

c. Visibility of positive vs. negative pips. At optimal screen brightness, negative pips are usually superior to positive pips. This is not true for dimmer screens.

d. Pip visibility centered vs. offcentered operation. At optimum tube brightness and above, the centered condition resulted in (significantly) best visibility. The general rule appears to be that the more offcenter the tube is, the poorer is the visibility. The significant interaction between degree of offcentering and tube bias indicates that visibility thresholds did not show the same pattern at each bias over the three degrees of offcentered operation tested.

Source: Scott, 1957.

Source conditions: Done at an operational unit, radar (AN/FPS-3 with 12DP7 tube), antenna rotation rate (3.3 rpm), pip dimensions (2 degrees x 1 microsecond), PRF (200 pps), pip source (single target generator--trigger voltage, PRF, and antenna rotation rate were fed to both the simulator and the display unit from normal channels on site), illumination at tube face (.1 fc), pip locations (.7 maximum range from rotational centre of sweep-line and 0 degree azimuth--pips appeared in a 1 inch square drawn on tube face), subjects (20 trained radar operators).

e. PPI pip visibility and beam width (7BP7). Figure 58 shows the relation of pip visibility to pip length. Beam (lobe) width is varied from 12 to 60 degrees. Visibility thresholds for the 12 degree pip were taken as a reference point. Visibility improves as pip length (beam width) increases. Gains in visibility accelerate faster when the shorter beam widths are used.

Source: Bartlett and Williams, 1947.

Source conditions: Tube (7BP7), PRF (600 pps), pip produced by taper gating a 2 microsecond pulse over 20 degrees of the PPI, visual angle subtended (6"--70 x 3.5 minutes, 24"--280 x 14 minutes), dim screen (-20 volts CRT bias), bright screen (not given--probably -17 volts bias), range scale (20 miles), pip location (1/4 and 3/4 radius), CRT screen brightness ("optimum"), noise (nil), subjects (3--trained).

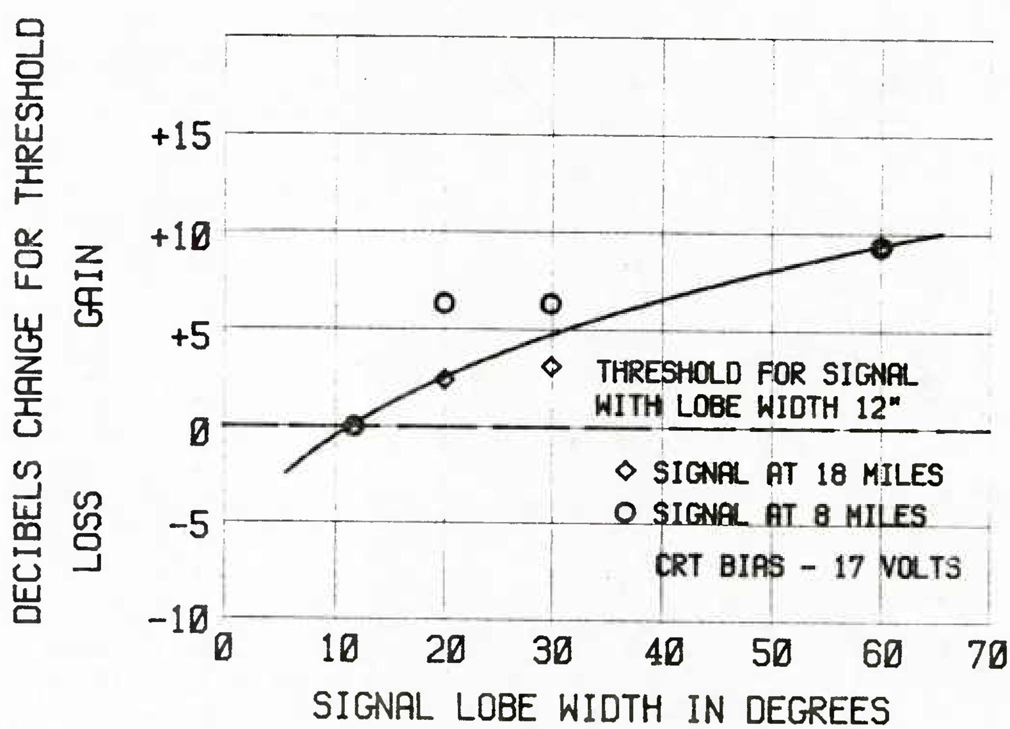


Figure 58. Relation of pip visibility to pip length.

f. PPI pip detectability and pulse length (VCR 516). Figure 59 shows pip detectability as a function of pulse length for the VCR 516 PPI. The four pulse length settings used were measured on the A-scope and converted to the PPI. The spot size (1.5 mm) widened them further.

Increases in pulse length resulted in marked increases in detectability. Detectability improved by nearly 3 dB for each doubling of pulse length.

Increased pulse length was accompanied by increased pip brightness and the figure actually shows the combined effects of increased length and brightness.

Source: Craik and Macpherson, 1945.

Source conditions: Tube (VCR 516--9 inch diameter), run at (5500 volts), sweep rotation rate (4 rpm), PRF (400 pps), spot size (1.5 mm), range (40,000 yards), pulse length when not being varied (3.4 microseconds), range scale (1.5 cms represented 10,000 yards), noise (used--not defined).

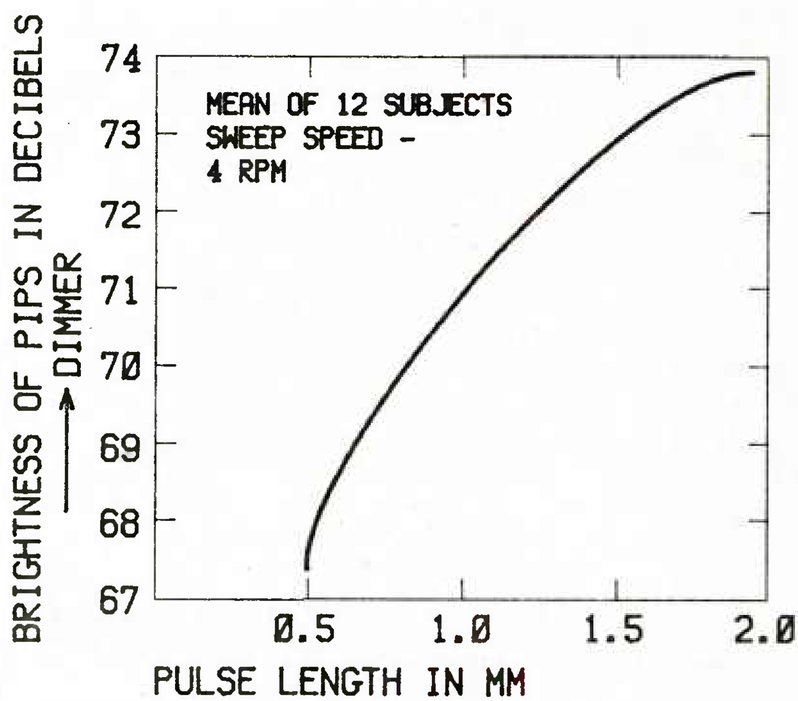


Figure 59. Pip detectability as a function of pulse length.

g. PPI Pip detectability as a function of pip length (with noise). As pip length increases, detectability threshold improves (decreases). This is to be expected for two reasons: (1) for small areas, visibility varies directly with target area, and (2) the smaller (shorter) the pip is, the more likely it is to be confused with a noise spot.

Source: Crawford, 1950.

Source conditions: PPI (simulated ultraviolet light painted rotating sweep-line and changing noise background on the phosphor screen--pip projected onto screen independently; pip position (randomized), noise patterns (3, "moderate," "normal," excessive"); subjects (5--further information lacking).

h. PPI pip visibility and range scale (7BP7).

(1) There is a steady improvement in visibility as pip thickness is increased by switching to shorter range scales.

(2) Noise conditions tend to lessen the advantage due to thicker pips (cf. a maximum advantage of 10 dB vs. 8 dB for the noise-free condition, when switching down from the 200- to the 4-mile range scale).

(3) The decreasing changes in screen brightness that occur when switching downward from the 200-mile range scale result in even greater gains in visibility than does increasing pip size.

(4) The optimal range scale for visibility depends upon CRT bias (and the optimal CRT bias depends upon range scale).

Source: Bartlett and Williams, 1947.

Source conditions: PRF (200 pps), beam width (14 degrees), range scales (4 to 200 miles), noise (1.53 volts rms), viewing hood used, remainder as in 3.17.e.

i. PPI pip visibility and pip range position (7BP7) (A). The radial position (range) of a pip is like pulse length and beam width, inasmuch as it helps determine pip size. Generally, the greater the target range is, the larger is the pip. Pip range, like antenna rotation rate and PRF, also a determines pip brightness.

When pips are large and screens dim or optimum, visibility tends to increase very gradually with increase in range. In the case of the large bright pip, visibility increases 2 or 3 dB in going from 1/8 to 1/2 radius and then decreases about 2 dB from 1/2 to full radius.

When pips are small and screens bright, however, range is a factor in pip visibility.

Source: Morgan, 1952.

Source conditions: Tube (7BP7), antenna rotation rate (10 rpm), PRF (600 pps), pip location (1½ radius), pulse length (2 millisecond), beam width (30 degrees), viewing distance (12 inches), noise (nil).

j. PPI pip visibility and pip range position (7BP7) (B).

(1) There is no systematic relation between pip range position and visibility.

(2) Pip size changes with range position and also is an important factor in visibility. Apparently the increase in pip length (with increasing range) is compensated for almost completely by the corresponding screen brightness decrease, at least for relatively large pips.

(3) Generally, with large pips, visibility is independent of radial distance of the pip from screen center.

Source: Bartlett and Williams, 1947.

k. PPI pip detectability and high-speed antenna rotation rates. Figure 60 shows the signal strength in microvolts required for the 50 percent pip detectability threshold as a function of antenna rotation speed, for two different phosphor-coated tubes.

(1) At all antenna rotation speeds the long-persistence P7 phosphor is superior to the short persistence P11 phosphor (a difference of from 2.5 to 4.8 dB).

(2) Detectability threshold appears to be unaffected by antenna speed with the P11 phosphor.

(3) Detectability threshold, with the P7 phosphor, deteriorates with increased antenna speed up to about 1200 rpm, where it begins to improve. This drop probably results from integration by the eye between scans. At 1200 rpm, the time between scans is 1/20 second, which is about the length of time that the eye can retain an image.

(4) It can be generally concluded that, in the presence of sea clutter, "the lowest tolerable antenna speed and a long persistence screen should be used for the detection of weak signals" (e.g., snorkels). However, it should be noted that the simulated sea-clutter signal used in these tests had no sweep-to-sweep coherence. Signals with such coherence might result in a different conclusion.

Source: Grant and Ferris, 1952.

Source conditions: Tube (both P7 and P11), PRF (7000 pps), pulse length (2.2 microsecond), beam width (4 degrees), sweep length (6 miles), background (simulated sea clutter with background noise, found "best" by photographic comparison), antenna rotation speed (varied between 6 and 3000 rpm), pip presentation period (1 minute), pip position (randomized—any one of 16), subjects (5—further information lacking).

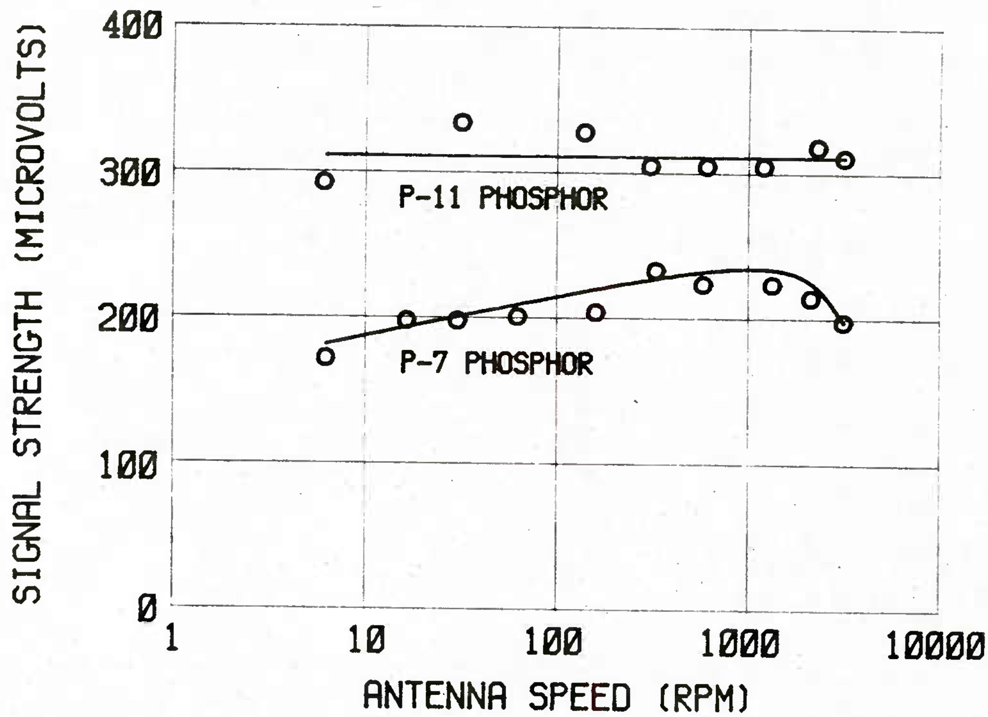


Figure 60. Pip detectability as a function of antenna rotation speed.

l. PPI pip visibility and pulse repetition frequency.

(1) For a bright screen (-14 volts bias), visibility increases with PRF up to approximately 500 pps and then remains fairly constant.

(2) For dim screen (-10 volts bias), increasing the PRF results in a more gradual increase in visibility. Peak visibility here is achieved at about 600 pps for the slower antenna rate. With the faster antenna rate, however, visibility continues to improve up to the highest PRF tested.

(3) It should be pointed out that visibility is not dependent upon PRF per se, but rather upon various brightnesses consequent to different PRF's.

(4) The slower antenna rotation rate permits superior visibility, because a slow rate allows more time for phosphor excitation on successive sweeps. The same is true of PRF.

Source: Williams, 1949b.

Source conditions: Tube (7BP7), antenna rotation rate (10 rpm), PRF (667 pps), pulse lengths and beam widths respectively (15, 2, and ½ millisec; and 30 degrees, 2 degrees, and 1 second).

m. Focus, bias, and PPI visibility. Table 17 shows the results when the "best focus" of the sweep line, in volts, was set at each of five CRT bias levels (VRI to -14 volts). The threshold pip intensity was determined at the "best focus" and at each of six other focus voltages, three greater and three less, from 168 to 322 volts.

Defocussing has practically no effect on visibility when a dim screen (VRI) is employed (loss of 1 dB), but has a marked effect with a bright screen (loss of 17.5 dB).

Source: Williams, 1949b.

Source conditions: Pulse dimensions (.5 millisecond x 1 degree), subjects (1--"trained"), remainder as given in paragraph 3.17.l.

n. PPI pip detectability time as a function of pip brightness. Figure 61 shows the dependence of pip detectabiilty time on pip intensity.

(1) It is evident that pips close to threshold value require a much longer detectability time than those a few decibels stronger.

(2) On the average, pips at threshold and 2 dB above threshold were not detected within 120 seconds.

(3) The greatest time loss (40 seconds) occurs when pip intensity drops from 6 to 4 dB above threshold.

(4) The time loss at 14 dB (2.57 seconds) is not necessarily minimal as searches were begun without reference to the sweepline position (i.e., time sometimes elapsed before the pip was exposed).

Source: Harriman, 1950.

Source conditions: Tube (7BP7), sweep rotation rate (30 rpm), PRF (667 pps), viewing distance (12 inches), CRT bias voltage (5.5 volts below VRI), noise (nil).

Table 17

Focus, Bias, and PPI Visibility

	Item	VRI (Dim)	-20v	-18v	-16v	-14v (Bright)
a.	"Best focus" voltage set by operator	219	203	209	211	215
b.	Focus voltage giving best visibility of pip	202	180	209	196	215
c.	Visibility advantage of (b) over (a)	1 dB	1 dB	none	1 dB	none
d.	Visibility score at (b) in dB signal voltage	31	36	42.5	44	42
e.	Visibility score with extreme defocussing	30	32.5	34.5	31	24.5
f.	Visibility loss due to defocussing: (d) minus (e)	1	3.5	8	13	17.5
g.	Average deviation of visibility scores (N = 7)	.3	.8	2.1	3.7	3.3

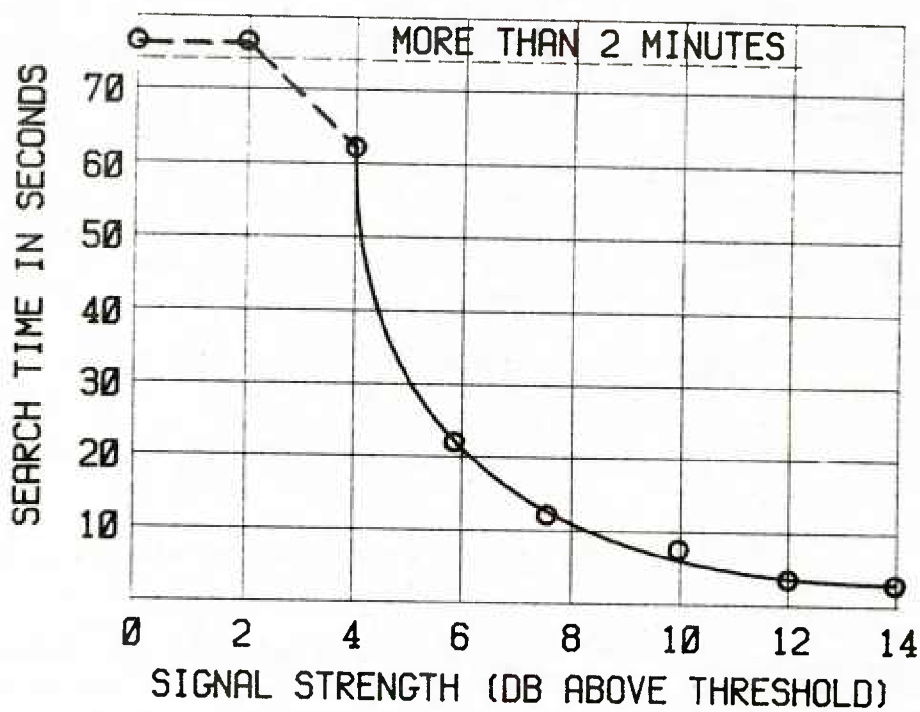


Figure 61. Relation between pip detectability and signal strength.

o. Visibility of PPI pips seen at different intervals after excitation. Figure 62 shows pip visibility as a function of time of viewing threshold pips after phosphorous light decay has preceded for various intervals (i.e., as a function of time after initial pip excitation).

(1) Visibility for immediate pips is better at a bias of -17 volts than at any of the others tested.

(2) Beyond 7 seconds, greatest visibility occurs at -20 volt bias.

(3) Duration of pip visibility for intense pips depends on bias. In general, the higher the CRT bias is, the longer is the persistence of the pips from strong signals. At 0 dB, persistence of visibility at biases of -11, -14, and -17 volts was 21, 22, 63, and 196 seconds respectively.

(4) The biases of -11, -14, and -17 volts have parallel functions of visual decay. The -20 volt bias, however, results in an initial drop in visibility, followed by constant visibility for about 10 seconds, followed by deterioration similar to the other biases.

Source: Sweet and Bartlett, 1948.

Source conditions: Tube (7BP7), PRF (600 pps), antenna rotation (10 rpm), pulse length (2 microsecond), beam width (20 degrees), viewing distance (12 inches), pip location (3/4 radius due south of center), viewing hood used, subjects (5--male college students).

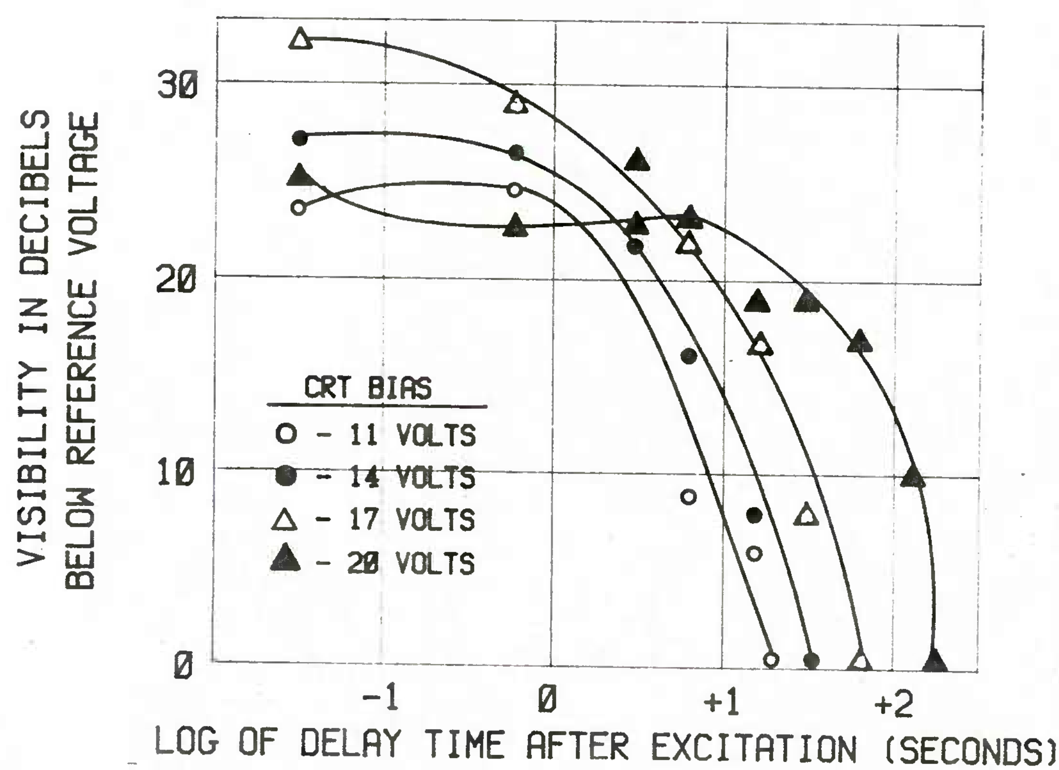


Figure 62. Pip visibility as a function of time after excitation.

p. Amount of surrounding illumination (VCR 516-PPI). Figure 63 shows the effect of varying illumination surrounding the CRT on pip detectability for antenna speeds of 60 and 4 rpm respectively.

(1) Figure 63a shows that .01 fc appears to be optimum for detectability purposes. The 1 fc detectability is significantly worse than the others, which show no significant differences.

(2) Figure 63b shows results similar to the first. The 1 fc illumination was significantly poorer than .01 fc, but not significantly poorer than .1 or .001 fc.

(3) It can be generally stated, then, that detectability is improved when there is a slight amount (less than 1 fc) of surrounding light.

Source: Craik and Macpherson, 1945.

Source conditions: Tube (VCR 516--9 inch diameter), run at (5500 volts), sweep rotation rate (4 rpm), PRF (400 pps), spot size (1.5 mm), range (40,000 yards), pulse length when not being varied (3.4 microsecond), range scale (1.5 cm represented 10,000 yards), noise (used--not defined), subject 12--"RAF pilots under training"). Same as given in paragraph 3.17.f.

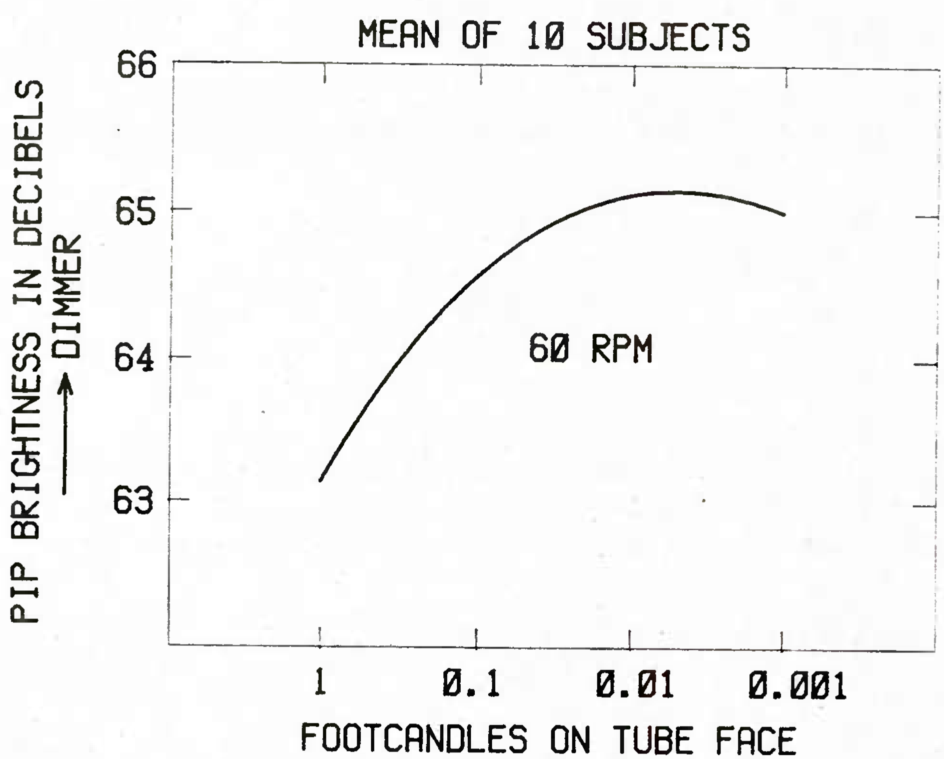


Figure 63a. Antenna speed = 60 rpm.

Figure 63. Pip detectability as a function of ambient illumination of tube face.

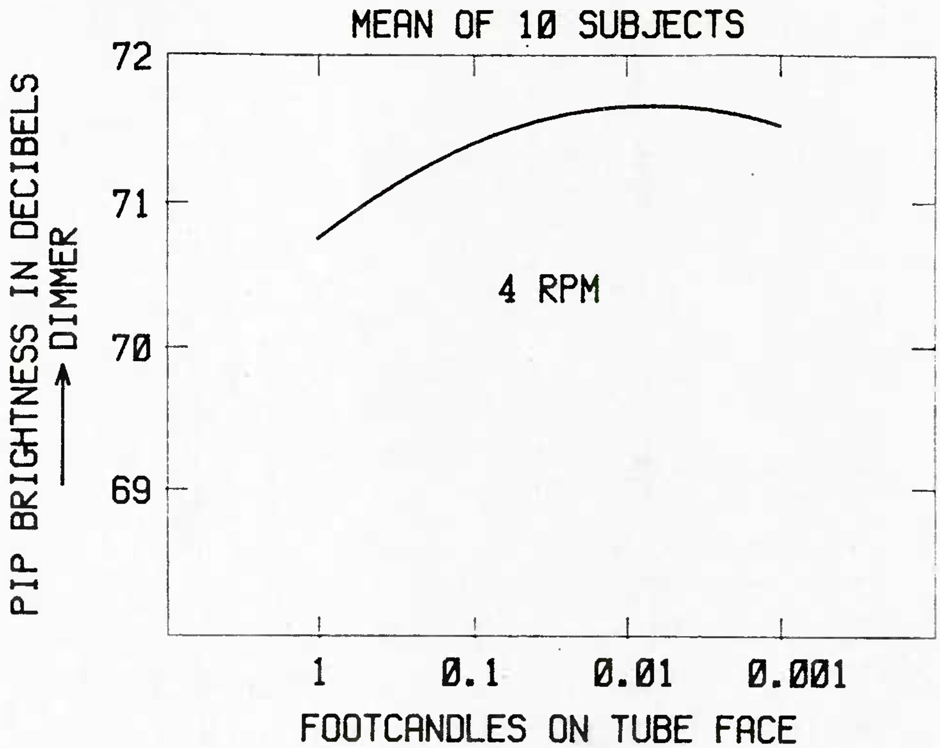


Figure 63b. Antenna speed = 4 rpm.

q. Amount of color and surrounding illumination (7BP7). Figure 64 shows pip visibility as a function of amount of surrounding illumination for several colors of illuminating light.

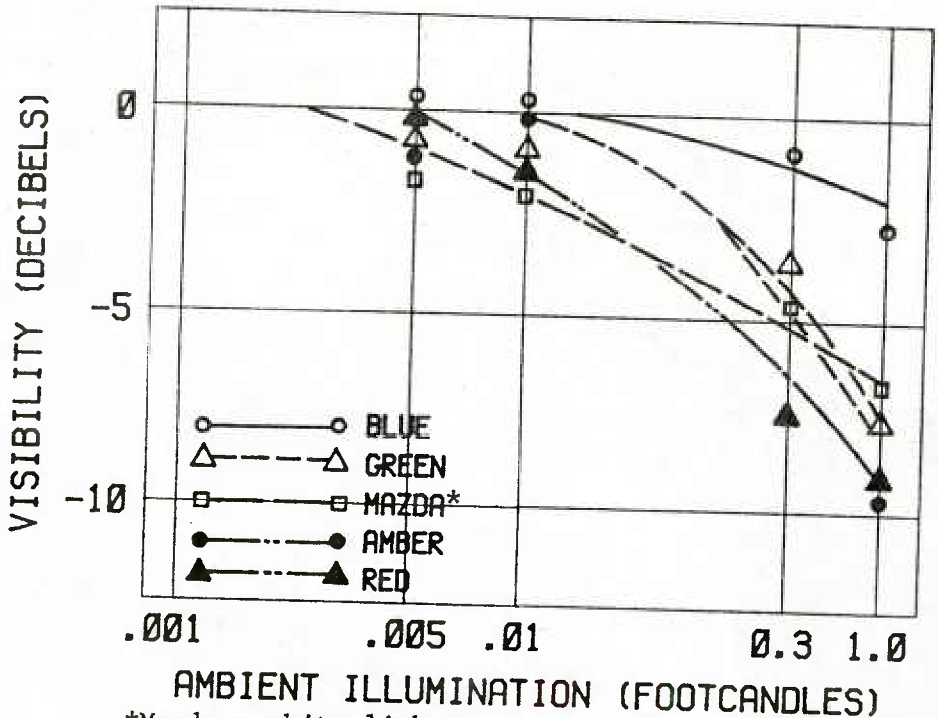
(1) Visibility decreases (thresholds increase) as ambient illumination increases. (Statistical analysis of the data shows that illumination by blue light can be as high as .5 fc before significant impairment occurs. The other illuminants result in significant losses at or below .5 fc.)

(2) Visibility impairment is least for blue light and most for red light.

(3) It should be noted that degree of impairment seems to be positively correlated with illuminant wavelength.

Source: Williams and Hanes, 1949.

Source conditions: Tube (7BP7), viewing distance (12 inches), pulse length (2 microsecond), beam width (2 degrees), sweep rotation rate (20 rpm), PRF (1000 pps), noise (nil), screen brightness (-17 volts bias), pip locations (1/3 screen radius), subjects (2--further information lacking).



*Mazda = white light.

Figure 64. Pip visibility for different hues.

r. Surrounding illumination vs. darkness. Figure 65 permits a more precise determination of the nature of the decrement between .1 and 1.0 fc. An optimum bias of 7 volts from VRI was employed.

(1) There is a steady and apparently linear decrement in pip visibility when ambient illumination is increased from .1 to .3 fc.

(2) A slight statistical interaction (p = .05) was found between CRT bias and ambient illumination.

(3) Whereas one study suggested that some illumination yields a slight advantage over operation in the dark, these data fail to show any such advantage (nor disadvantage up to .1 fc).

Source and source conditions: Same as given in paragraph 3.17.q.

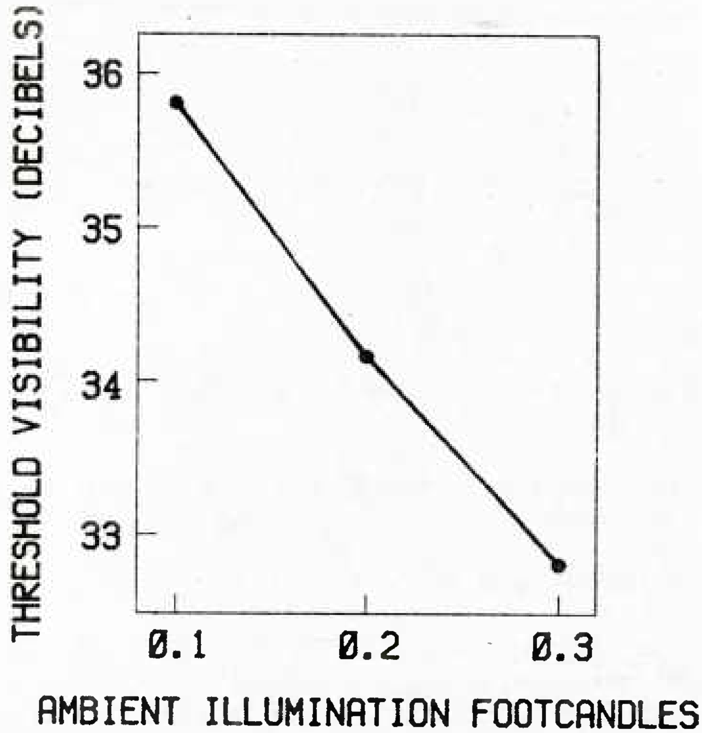


Figure 65. Pip visibility as a function of ambient illumination.

s. PPI pip detectability and viewing distance (VCR 516). Figure 66 shows the effect of viewing distance (CRT tube to eyes) upon pip detectability. Under these particular experimental conditions, the optimum viewing distance was 18 inches. Detectability was poorer when viewing distance was greater or less than 18 inches, although the differences shown are not statistically significant by the "t" test.

Source and conditions: Same as in paragraph 3.17.p.

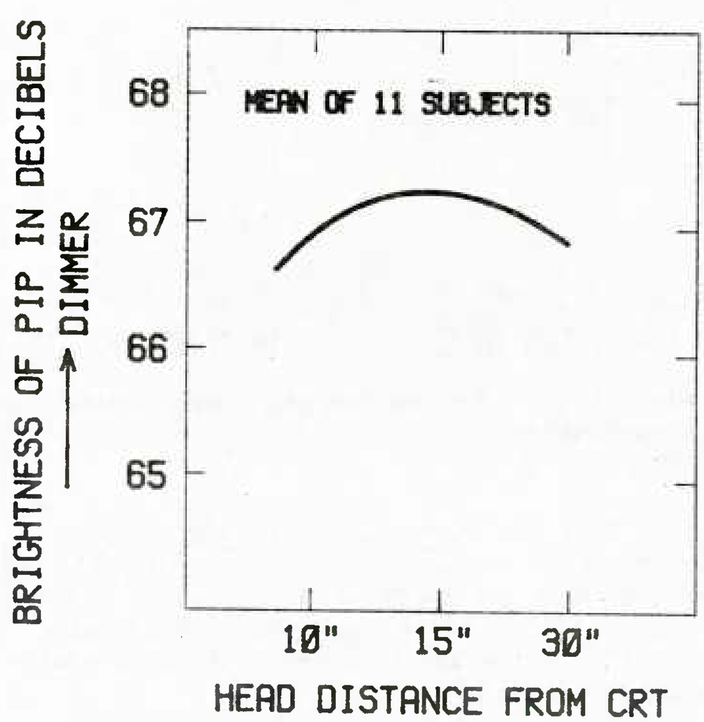


Figure 66. Pip detectability as a function of viewing distance.

t. PPI pip visibility and viewing distance (7BP7). Figure 67 shows pip visibility thresholds for viewing distances of 6 and 24 inches, at each of two screen brightness levels.

(1) With no noise and the dim screen, the advantage of the 6 inch over the 24 inch viewing distance is more than 8 dB.

(2) With no noise on a bright scope, the advantage of the 6 inch viewing distance is more than 5 dB.

(3) The advantage of the 6 inch viewing distance is either reduced or eliminated when noise is present.

Source: Bartlett and Williams, 1947.

Source conditions: Tube (7BP7), PRF (600 pps), pip produced by taper gating a 2 microsecond pulse over 20 degrees of the PPI, visual angle subtended (6"--70 x 3.5 minutes, 24"--280 x 14 minutes), dim screen (-20 volts CRT bias), bright screen (not given--probably -17 volts bias), subjects (3--trained).

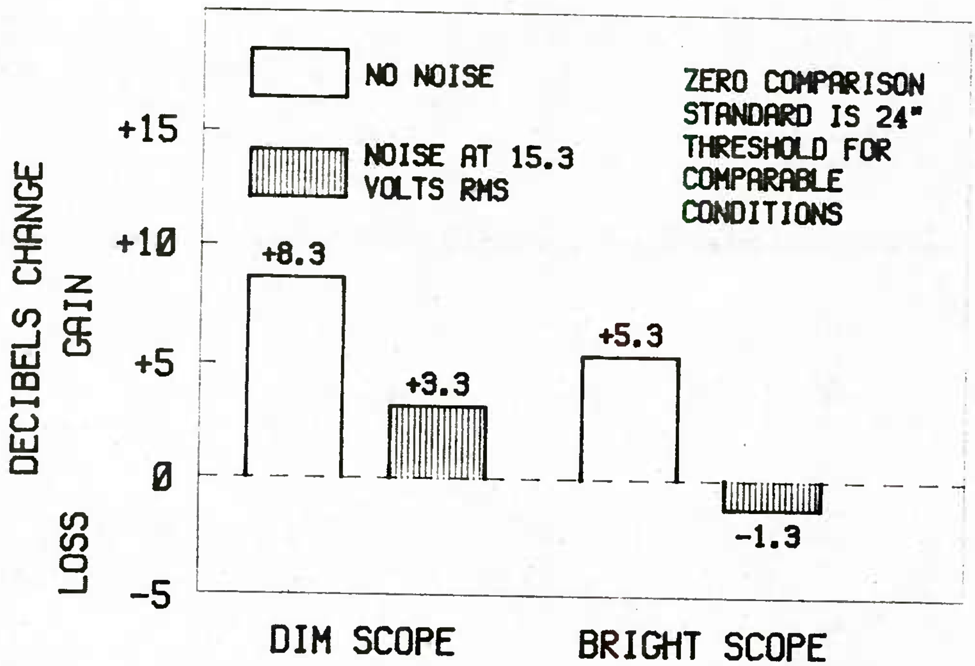


Figure 67. Pip visibility as a function of viewing distance, noise, and scope brightness.

u. Effect of CRT screen brightness on night vision. Figure 68 shows the relation between the threshold background brightness required to see a black disc subtending .5 degree at the eye and the glare illumination at the eye produced by a CRT in the field of view and 30 degrees below the point of observation. Data are shown for green, yellow, and red CRT screens and for three average sweep-line brightnesses, .026, .042, and .200 candle per square foot.

The effect on night vision of a CRT in the field of view of an observer is less for a yellow than for a green screen and less for a red than for a yellow screen. It is approximately proportional to glare illumination at the eye. (Illumination at 16 inches from the screen for constant screen brightness decreases with increasing dominant wavelength.)

Source: Tousey, 1944.

Source conditions: Screen pattern chosen to approximately an A-scan search radar in area, complexity and brightness; moving pattern (1½ x ½ inches in size), viewing distance (16 inches), screen brightness measurements (Macbeth Illuminometer), background (white screen 10 feet from observer, subjects (6--further information lacking).

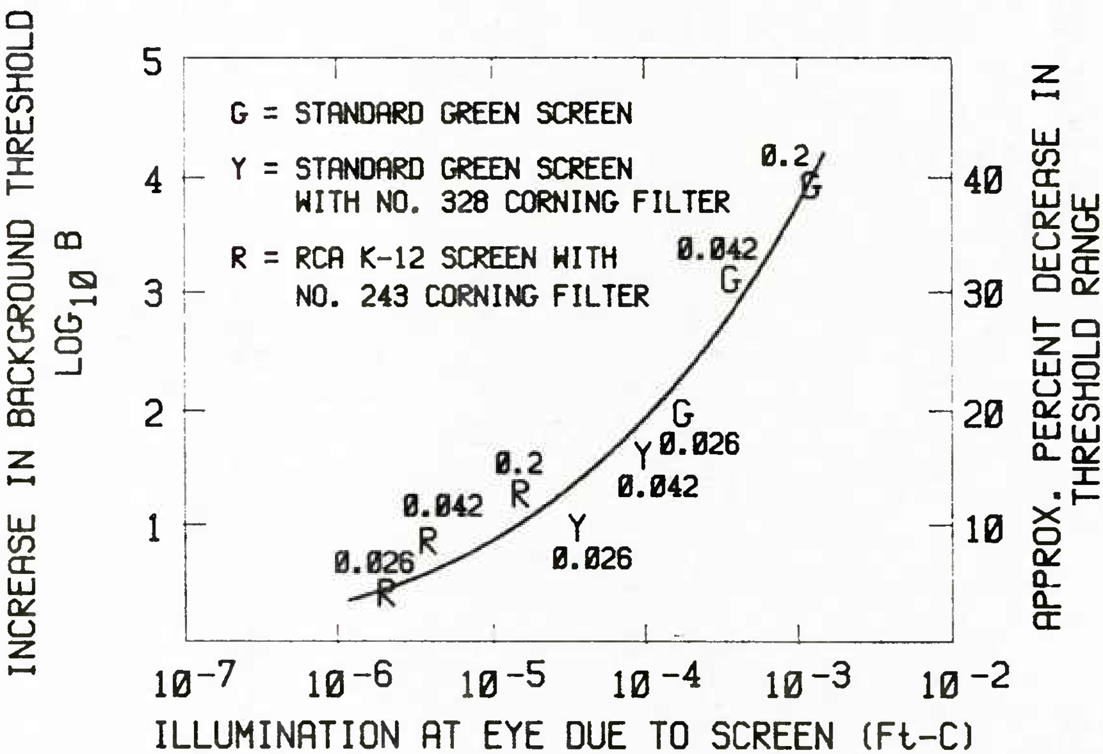


Figure 68. CRT screen brightness and night vision.

v. Visual acuity at near distances and proficiency of radar operation. Figure 69 shows the relation between near visual acuity scores and ratings of radar operating proficiency for 73 short-term and 84 long-term operators respectively. A score of 1.0 corresponds to the vision of the "standard (20/20) eye." Scores greater than 1.0 indicate above average performance.

(1) Operations with substandard acuity were rated lower, on the average, than operators with standard or better visual acuity.

(2) The significance of the differences between average ratings for substandard and standard or better acuity scores were computed for both groups. The difference was highly significant for the short term group (CR = 3.85, indicating that there is less than one chance in 1000 that the difference could have occurred by chance). For the long term group, a CR of 1.69 was obtained, which is not statistically significant.

Source: Lindsley, 1944.

Source conditions: Measurements made with the ortho-rater.

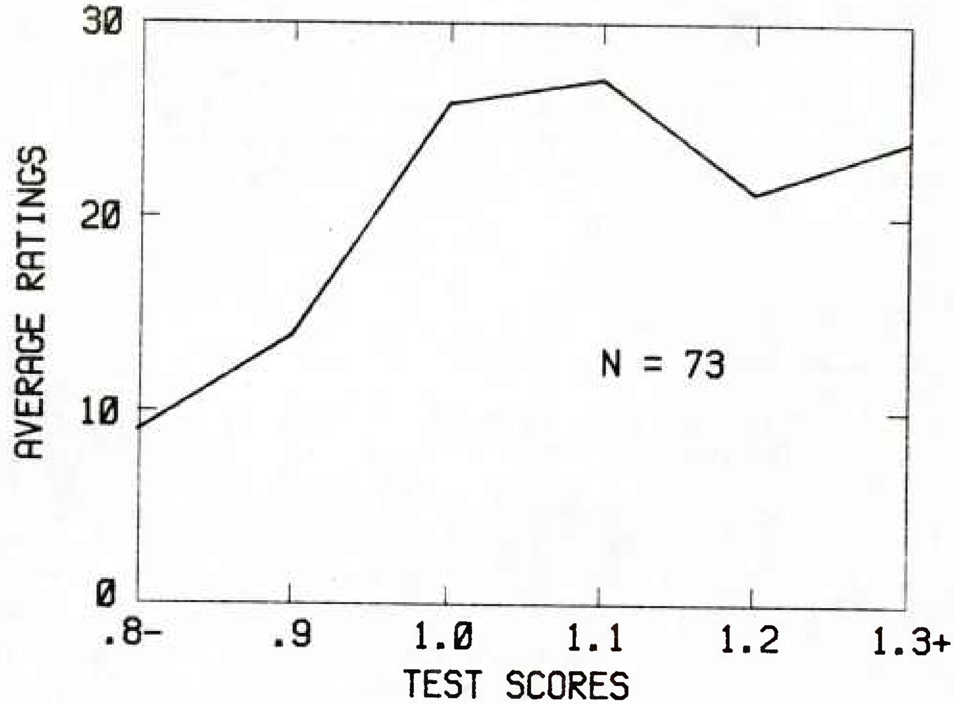


Figure 69a. Short-term operators.

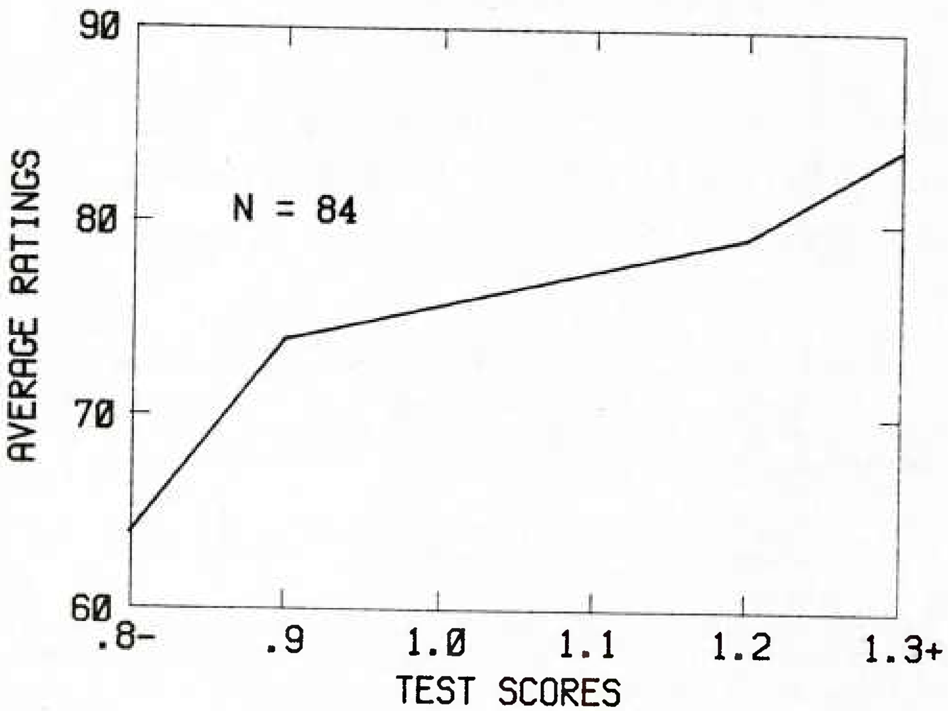


Figure 69b. Long-term operators.

Figure 69. Visual acuity and radar operator proficiency.

w. Variability of PPI pip detectability scores. Ordinarily, when the detectability of a pip is being determined for a particular set of conditions, the scores are not alike, but are distributed around the average (mean) score in a symmetrical fashion. The usual measure of this variability is the standard deviation (SD), defined as the root-mean-square deviation. Two standard deviations include two-thirds of all the scores. Figure 70, which illustrates this principle, shows a distribution of detectability scores in decibels attenuation of a reference signal for one experimental condition (not given). One SD here is 1.8 dB and 2 SD (3.6 dB) include two-thirds of all the scores. A SD of 1.0 dB would indicate that the distribution was much narrower and the average score more reliable.

Source: Garner and Hamburger, 1947.

Source conditions: Tube (4AP10), VG remote indicator (25 inch diameter), radar (SG), modulation (positive signals applied to grid), antenna rotation rate (5 rpm), lobe width (20 degrees), pulse length (1.5 microsecond), and range scale (20 miles), PRF (500 pps), noise (60" on the A-scope of the SG, with full gain, while pips saturated the receiver at a level twice this high), subjects (6--trained service personnel). The VG gives a dark-trace display.

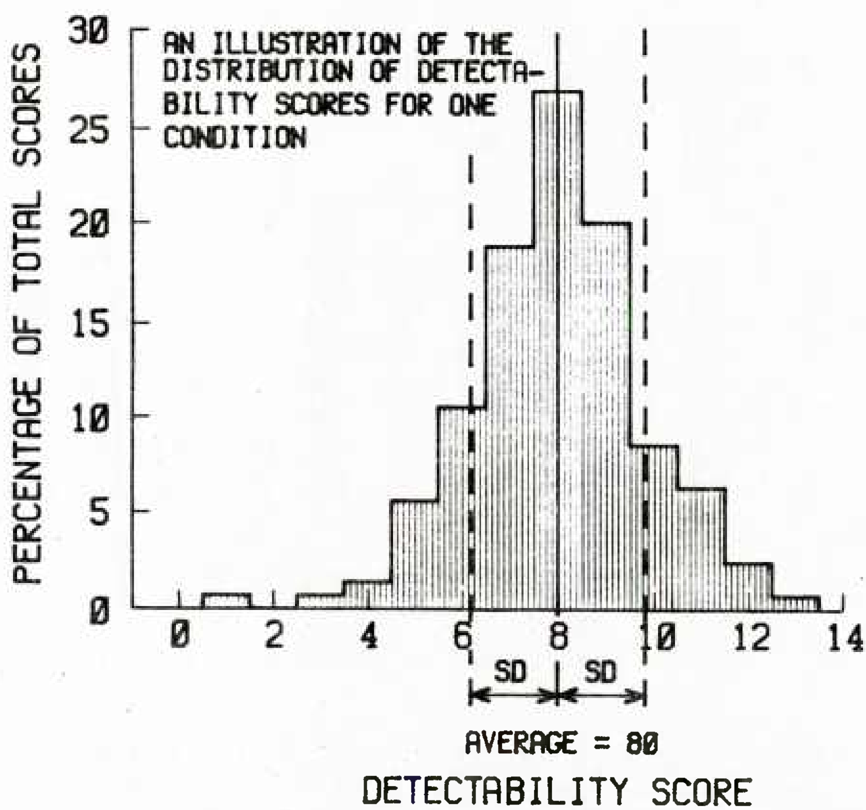


Figure 70. Variability in pip detection.

x. Average detectability scores and variability of detectability on the VG. Figure 71 shows how variability of scores is related to average detectability scores. A number of variability scores are grouped according to the average detectability scores for each group. Detectability scores are in decibels attenuation of a reference signal.

(1) The SD is considerably smaller for the high detectability scores than for the low detectability scores. That is to say, the more difficult it is to detect pips, the more variable are the detectability scores (i.e., the more variable are the values of signal strength at which pips are detected).

(2) There is nearly twice as much variability in detectability scores when the gain is -12 dB than when the gain is maximum. The difference in variability is greater than would be expected. The implication is that a high video gain is inherently able to reduce variability in detection of pips.

(3) Increasing the video gain decreases variability and decreasing CRT bias decreases variability. The relation holds not only for those cases where decreasing the bias increases detectability, but also for those where decreasing the bias further actually decreases detectability; for instance, when the video is very high.

Source and source conditions: Same as given in paragraph 3.17.w.

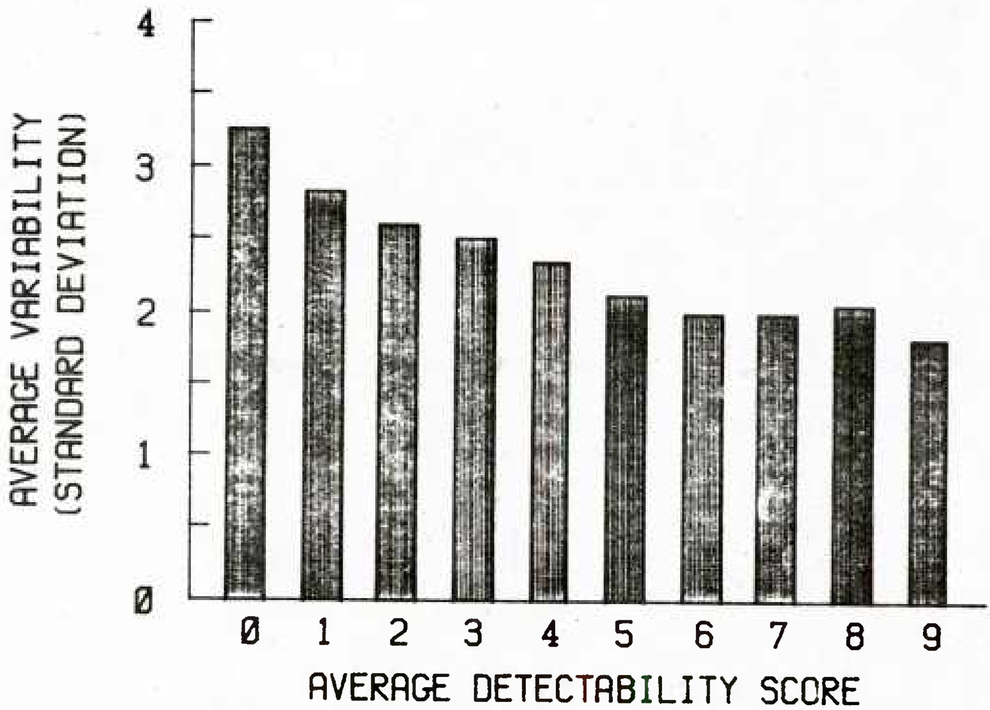


Figure 71. Relationship between pip detectability and variability.

y. Detection time as a function of number of pips (PPI). Figure 72 shows mean detection time of new pips appearing on a PPI as a function of the number of pips already on the scope. In obtaining these data, subjects were required to report target positions, courses, and speeds as rapidly as possible, and to plot target positions, in addition to reporting new targets.

The time required to detect the presence of a new pip on a PPI increases in a positively accelerating function as the number of pips already displayed increases.

Source: Lefford, 1950.

Source conditions: Display (IP-48 unit (12 inch PPI) of the APA/56 remote radar indicator, mounted in mockup of Lockheed Constellation Model 749 CIC airplane), number of range rings (10), maximum range (200 miles), bearing markers (radial reference lines at 30 degrees intervals; no bearing scale), target generation (Aircraft Target Generator 15-AM-1), procedure (report of detection of new pip given priority; range, bearing, course, and speed of each target reported "as frequently as possible," target positions plotted at the subject's "own option and convenience"), target speeds (100-600 knots), courses (varied through 360 degrees, no course changes), subjects (4--experienced).

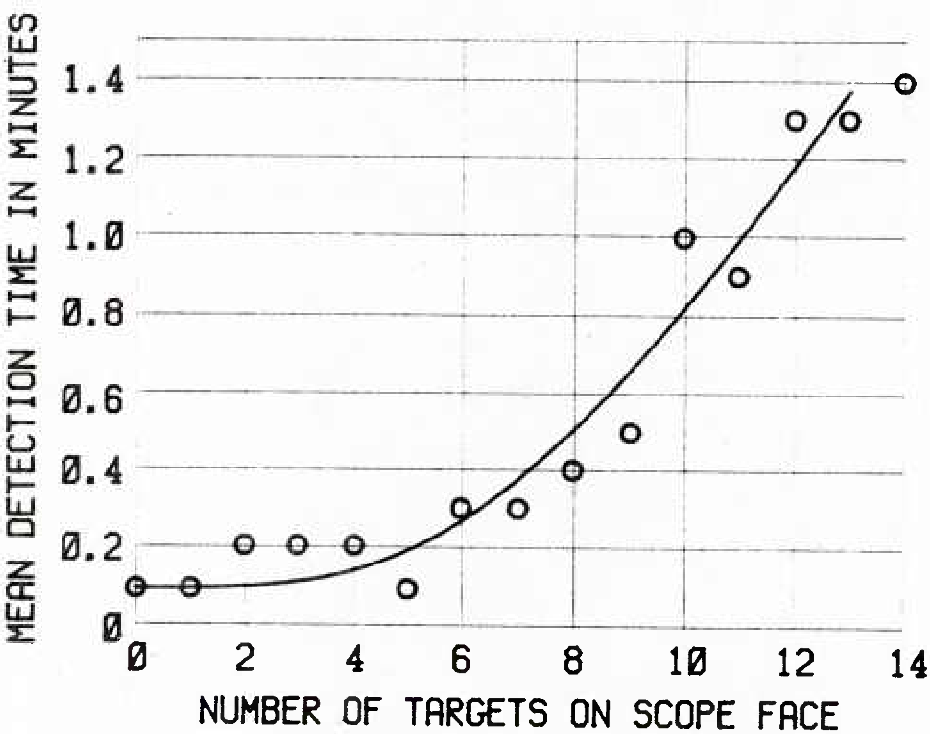


Figure 72. Detection time as a function of number of targets.

z. Detection of new pips as a function of time density of events (PPI). Figure 73 shows the relation between the time density of events occurring on a PPI and the probability of detecting, within a given time, the appearance of a new pip. (Time density is defined for the purposes of this experiment as the number of discrete target events occurring per unit time--the time unit used being 1 minute.) Data are shown for probabilities of detection within one, three, and six scans. Time density was increased concurrently with number of pips on the screen ("target load") and working time (one event occurred during each of the first 4 minutes; two, during the second four; etc.).

(1) The probability of detecting the appearance of a pip on a PPI within a given time decreases as the number of target events and the target load are concurrently increased through a working period.

(2) It appears that the curves may flatten out at a time density of about five events per minute or a target load of 13 to 14 pips on the screen.

(3) At higher target loads, increasing the rate of occurrence of target events (time density) tends to decrease the probability of detecting the appearance of a

new pip on the PPI. Therefore, time density, as a variable independent of number of pips, has some effect on detectability.

(4) As the number of pips displayed on a PPI is increased, the probability of detecting the appearance of a new pip decreases.

Source: Sinaiko, Lefford, and Taubman, 1951.

Source conditions: Display (IP-48 repeater console of the APA/56 remote radar indicator, in a full-scale mockup of the PO-1W airplane); sweep rate (6 rpm): length of sweep (200 scale miles); reference marks (30 degrees angle marks and 10-mile range rings); initial target position ("towards the periphery of the scope"); target speeds (300-590 knots; "faster targets introduced later"); courses (varied through 360 degrees but generally towards the center); procedure (immediate verbal reports of: new pips, fades, reappearances, IFF signals and course changes; range bearing course and speed of each target reported "as rapidly as possible").

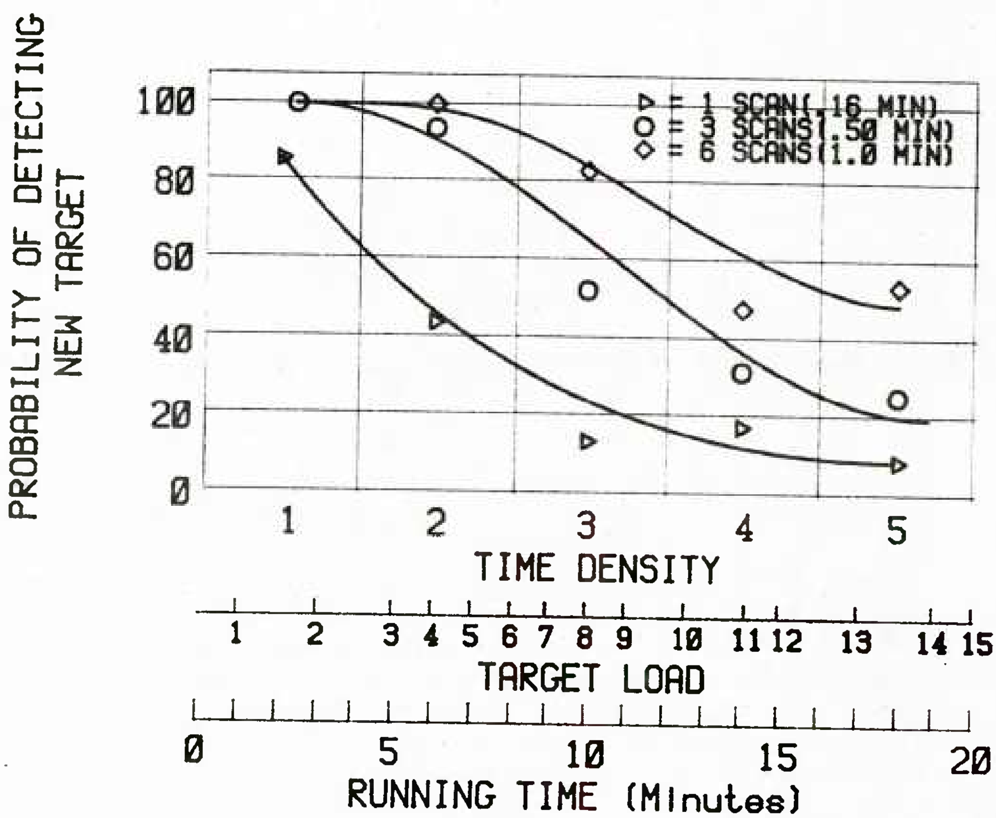


Figure 73. Detection as a function of time density of events.

aa. Detection time as a function of number of pips (PPI). Figure 74 shows the time required to detect a new pip on a CRT as a function of the number of pips already displayed. The time required to detect a new pip on a CRT is a negatively accelerated, increasing function of the number of marked pips already displayed. Detection time increases rapidly as the number of pips increases from zero to about six, but thereafter degree of saturation is unimportant. There is no apparent relationship between the time required to detect a new pip on a CRT and working time, up to 30 minutes.

Source: Thornton, 1954.

Source conditions: Display (VK-3, 10 inch PPI-P7 phosphor), antenna rotation rate (15 rpm), ambient illumination, measured at CRT (.10 fc), pip, strobe, and sweep-line brightness (well above threshold), noise (nil), pip shape and dimensions (3 degree arcs, 1 mm in thickness), pip generator (15J-1-C), viewing position (subject standing over horizontal screen 36 inches from floor), subjects (6--for each of Experiments 1 to 4, and 3 and 5 for the two conditions of Experiment 5).

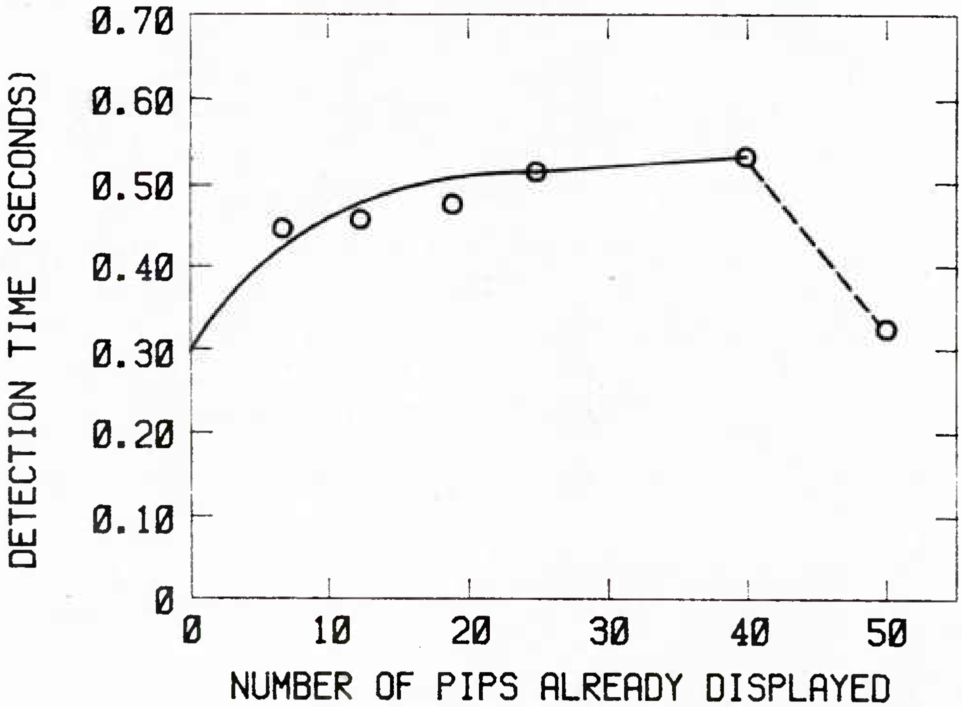


Figure 74. Detection time as a function of already displayed pips.

bb. Detection of course change as a function of time density (PPI). Figure 75 shows the relation between "time density" (1-5) and the probability of detecting, within a given time limit, a course change on the PPI. Data are shown for probabilities of detection within 1, 2, and 3 minutes.

(1) Time density increased concurrently with the number of pips displayed ("target load") and working time.

(2) The probability of detecting a change in course of a target from the PPI decreases as time density and number of pips increase through a working period.

(3) The probability of detecting a course change in 1 minute is very much less than any of the probabilities of detecting new pips, fades and reappearances, and IFF signals.

Source and source conditions: Same as given in paragraph 3.17.z.

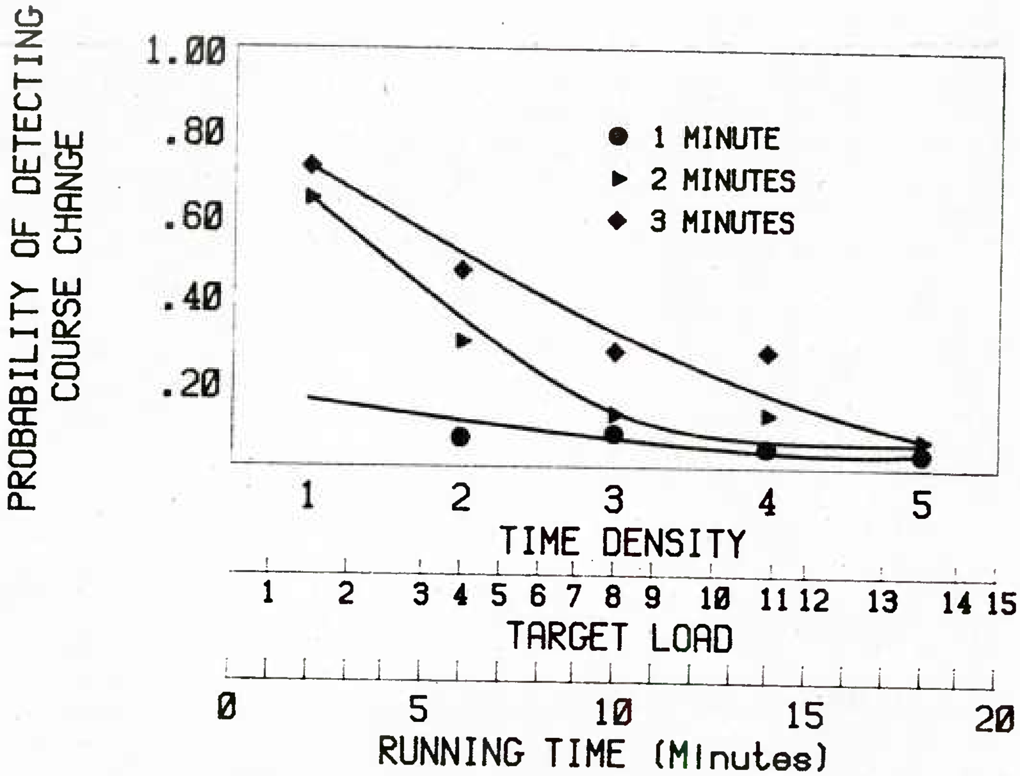


Figure 75. Detection of course change as a function of time density.

cc. Pip range position and detectability on the VG radar remote PPI. Figure 76 shows the effect of target range (distance of pip from screen center) on detectability with the VG radar remote PPI.

(1) Detectability is superior in the 10,000 to 30,000 yard range, and inferior at VG center or at the outside edge.

(2) Poor center detectability probably results from the increased screen darkening towards center (dark pips on a whitish screen) with resultant loss of contrast and also from the fact that pips are smaller near center.

(3) Poor edge detectability probably results from dimmer pips due to the increased angular velocity of the sweep-line. But this "edge loss" is rather abrupt to be explained solely in terms of sweep velocity. It is possible that there is also an "attention factor" involved (i.e., operators may tend to watch the sweep more closely in the middle ranges).

Source and conditions: Same as given for paragraph 3.17.w.

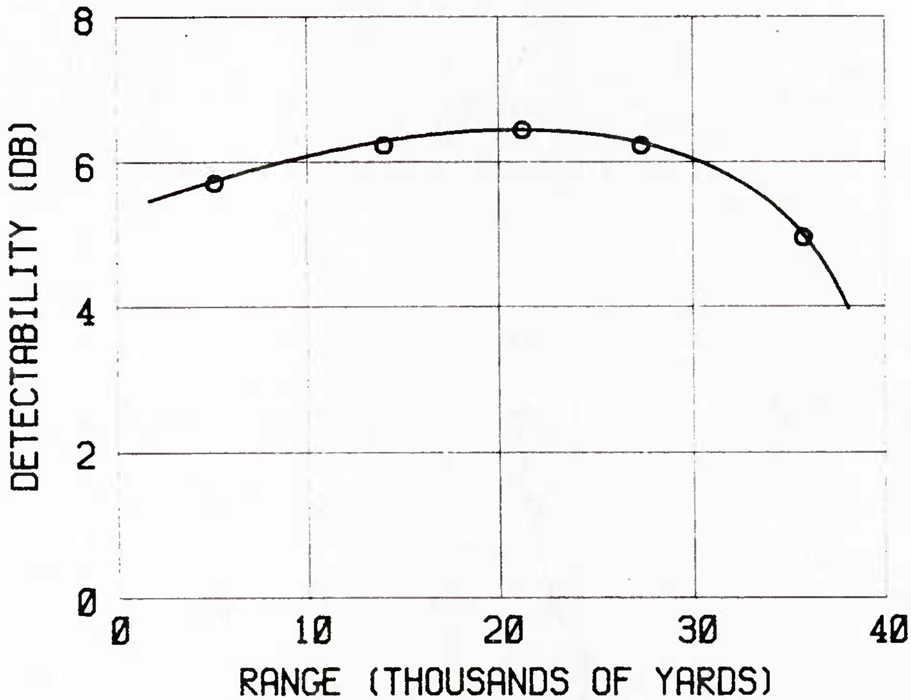


Figure 76. Target range and pip detectability.

dd. Bearing accuracy as a function of range (PPI). Bearing accuracy improves as target range increases. This tendency is most marked when bearings are estimated without the aid of a bearing cursor.

Source: Chapanis, 1949.

Source conditions: Displays (VJ--standard; VJ--standard with the addition of a bearing counter and new experimental range counters; criterion units--2 VF indicators), pips (stationary, 6 at a time), pip width (6 degrees), pip thickness (400 scale yards), range (10,000 to 40,000 yards), bearing (010 degrees to 350 degrees), range rings (4, at 10,000 yard intervals), antenna rotation rate (6 rpm), subjects (9--experienced, 2-week training period under experimental condtions).

ee. Target indication performance and CRT size (PPI). Figure 77 shows accuracy of estimating bearing (degrees) and range (miles) of a target from a PPI, as a function of scope size. Accuracy is measured in terms of number of "correct" responses (to the nearest degree and nearest mile), out of 36 possible correct responses on each screen.

Accuracy of estimating range and bearing from the PPI increases as CRT diameter is increased from 3 to 7 inches. The greatest improvement occurs as the diameter is increased from 3 to 4 inches. There is little improvement with increase of diameter beyond 5 inches. This relation is not affected by changes in the time available per pip.

Source: Horton, 1949.

Source conditions: Display (schematic PPI projected on an opal glass screen; black lines and numerals on white background, pre- and post-test exposure fields of brightness equal to test field), range rings (4, representing 40 miles), bearing scale (2 degree intervals with every 10 degrees numbered), radial reference lines ((1) every 10 degrees (2) every 20 degrees), pip (black), pip dimensions (2 scale-miles wide, 2 degrees in length at 25 miles range), subjects (240--male, no experience in radar, 20/20 vision).

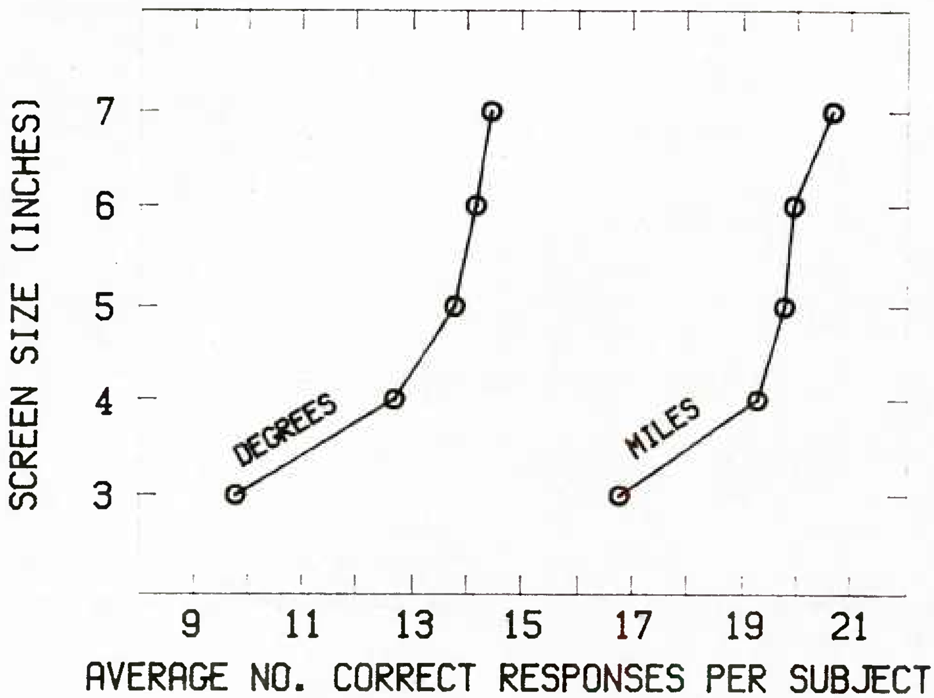


Figure 77. Bearing estimation and CRT size.

ff. Performance decrement in time, in range and bearing indication (PPI). Figure 78 shows percentage of reports correct, and rate of reporting through a 35-minute work period in determining bearing and range of targets from a PPI. There is some early decrement, followed by recovery and then by gradual deterioration. It is possible that the curve would level off if extended beyond 35 minutes. Rate of reporting does not vary significantly during a 35-minute work period. (In a 2-hour experiment under similar conditions, there was still no significant change--data not shown in Figure 78.)

Source: Murrell, 1951.

Source conditions: Display (photographic reproduction of live radar; size and type not specified), pip dimensions (30 degrees 3 scale miles), subjects (24--12 male, 12 female, experienced), no further data given.

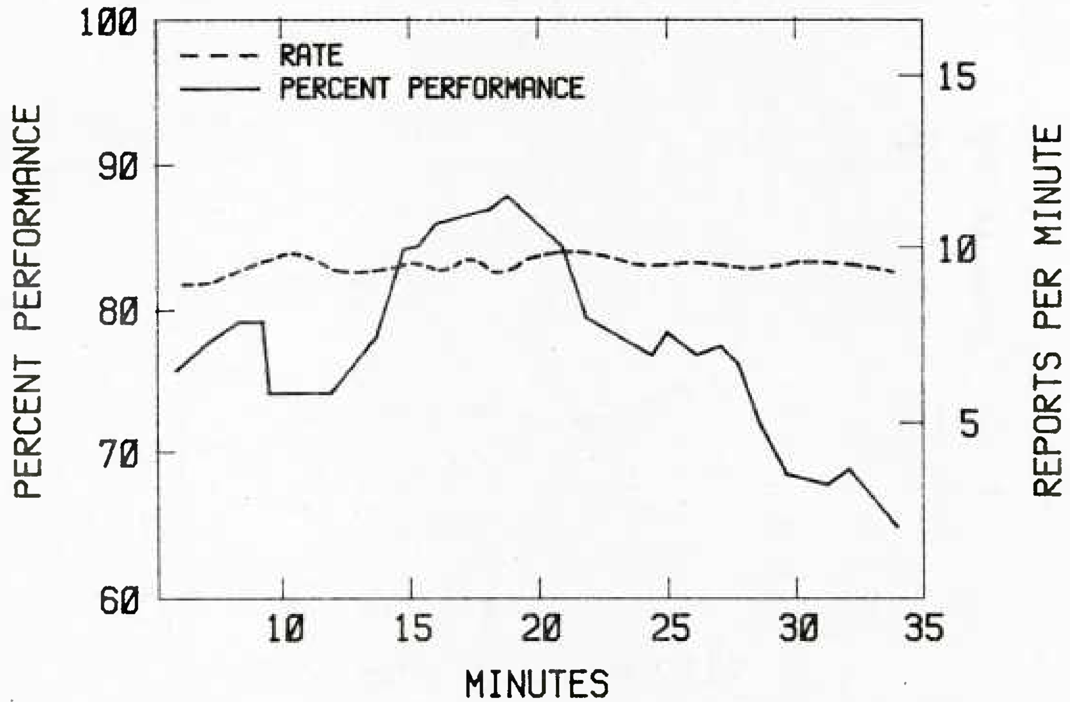


Figure 78. Reporting performance over time.

gg. Speed vs. accuracy in target indication (PPI). Figure 79 shows range error as a function of the number of times or the number of sweeps through which a pip is observed on the SG-1b (Mod 50) PPI. The data were obtained under different conditions of speed-accuracy instructions. Stressing accuracy with speed secondary has the effect of causing operators to observe a pip two or more times before reporting target position, as opposed to a single observation when speed is stressed.

The point at the extreme right side of the figure presents performance for the method of stopping the antenna trace over the target and determining range from the A-scope; number of pip observations in this case is defined as "infinity." Differences in accuracy between two, three, and four pip observations are not significant.

Observing a pip through two antenna trace sweeps results in a considerable improvement in accuracy over one observation; with more than two observations, there is no further significant improvement (although, of course, more time is required).

Source: Lipschultz and Sandberg, 1947.

Source conditions: Display (SG-1b (Mod 50) radar), pips (simulated by SRFL-1 target simulator; one at a time; stationary), pip dimensions (300 scale yards wide, 6 degrees long), limits of variation between successive pips (10 degree bearing, 5000 yard range), focus, gain, dial illumination (controlled by subject), subjects (5--experienced).

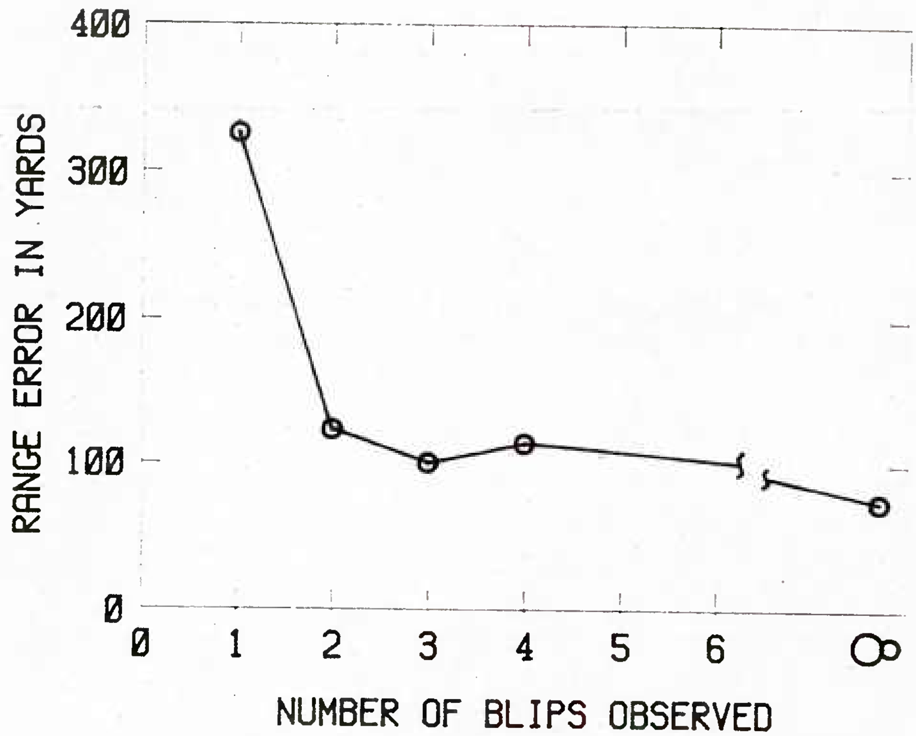


Figure 79. Error as a function of observation time.

hh. Pertinent factors. The following is also taken from Baker and Thornton (1957).

Some factors that result in poor performance:

(1) Instructing subjects to search in alternate fashions (e.g., "search in this manner, . . . now search in this manner . . . now search as previously").

(2) A decrement traceable to intense auditory noise has been demonstrated. Noise here refers to 100 dB throughout the task, with equal energy in all frequency bands from 100 to 5000 cps.

(3) Atmospheric temperatures affect vigilance. The optimum conditions appear to be a wet/dry reading of 75/85 degrees (effective temperature of 79 degrees F) with an air velocity of 100 feet per second. Effective temperatures of 70, 87, and 97 degrees F each resulted in fewer signal detections. Subjects were dressed in shorts only.

(4) "Restless" subjects--those who squirm more while watching for signals--tend to detect fewer signals than less "restless" subjects.

(5) Brief signals, and weak signals, result in a greater decrement than prolonged or strong signals.

Some factors that apparently do not affect vigilance:

(1) Briefing subjects beforehand to watch very carefully during a particular period of the task had no effect on performance.

(2) Neither visual acuity nor intelligence test scores appear to be related to performance.

Some factors that prevent decrement in vigilance:

(1) Alternation of a half-hour on radar watch, with a half-hour at some other task, prevents a fall-off in performance, at least over a two-hour period. On the other hand, if the person being spelled simply sits back and watches his alternate number at work, no benefit accrues from his rest.

(2) Feedback (knowledge of results) prevents decrement during watches up to 2 hours in length. Subjects were told, "yes, that is right" when they correctly reported a signal and "you missed one there," when they failed to report.

(3) A sudden telephone message (a plea for better performance), in the middle of a vigilance task produced an improvement which lasted half an hour. Subjects had been briefed beforehand to expect a message.

(4) Signals which are relatively simple to detect (i.e., are intense) result in less decrement than is the case for difficult discriminations.

(5) The more frequent the signals, the greater the percentage detected.

SECTION 4

CRT DISPLAY SYSTEMS: TELEVISION DISPLAYS

4.0 CRT DISPLAY SYSTEMS: TELEVISION DISPLAYS

4.1 Introduction

This section discusses random position and raster scan displays of the console type (single observer and group viewing).

4.2 Symbol Resolution

Performance studies indicate that for 99.5 percent accuracy of character recognition, the minimal acceptable vertical symbol resolution is 10 TV lines per symbol height (see Figures 80 and 81), (Baker & Nicholson, 1967; Kinney, 1965; Hemmingway & Erickson, 1969; & Shurtleff, 1966a).

The percentage of correct responses to be expected as a function of scan lines is shown in Figure 82.

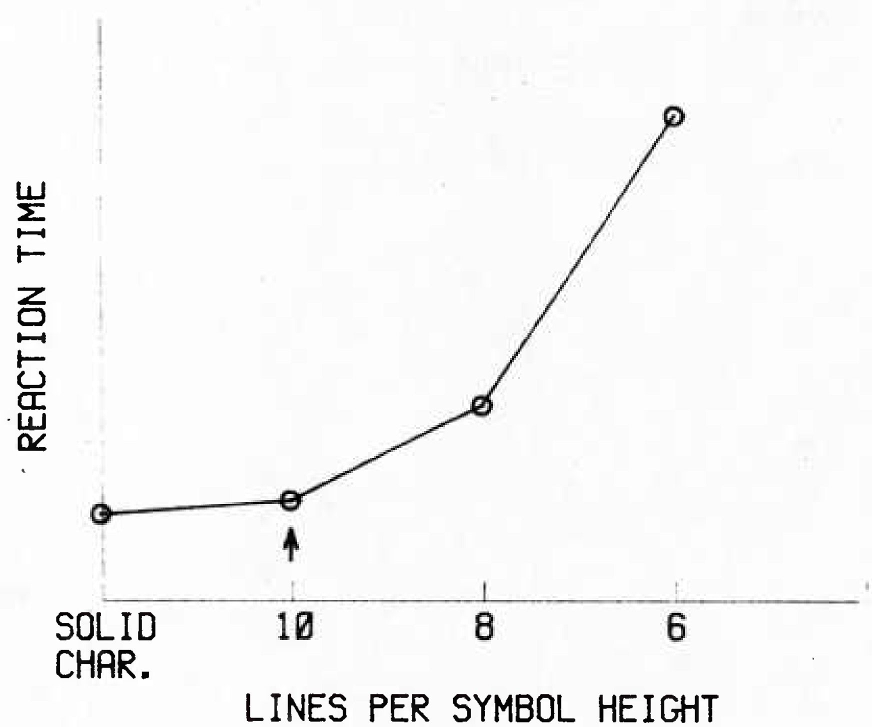


Figure 80. Speed of operator response as a function of number of scan lines.

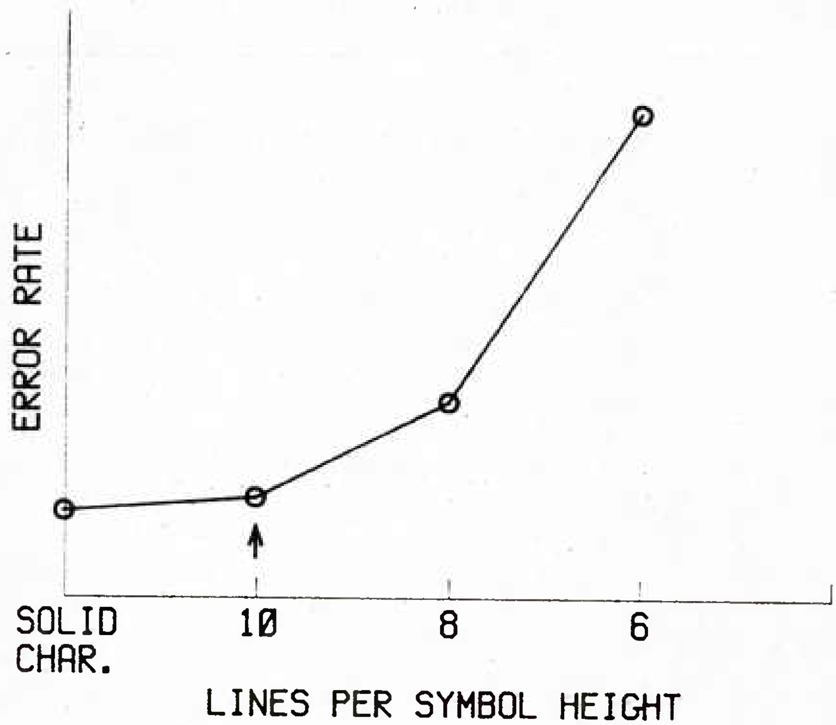


Figure 81. Operator error as a function of number of scan lines.

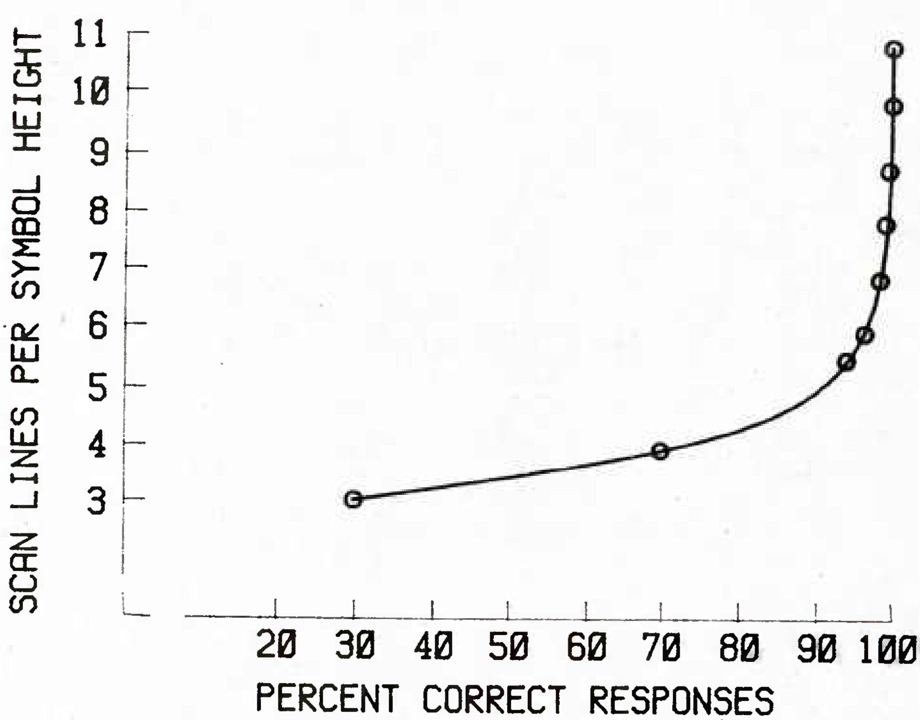


Figure 82. Accuracy of character recognition as a function of scan lines.

Those who want to display large quantities of data simultaneously (e.g., TV readout for computerized library system) commonly ask, "Can fewer TV raster lines be used per symbol height if the observer is allowed to view the display as closely as possible?" The answer is that, while accuracy can be maintained by greatly increasing the visual size for resolutions below 10 to 12 lines per symbol height, these size requirements are too great (e.g., 16 to 32 minutes of arc) to be operationally feasible, since, in many cases, to achieve these sizes, the display would have to be observed too closely for the near focal point of the eye (10 to 12 inches).

4.3 Symbol Size

The acceptable visual size for viewing televised symbols is between 12 and 15 minutes of arc (Shurtleff, 1966b). Figures 83, 84, and 85 shows the accuracy of identification as a function of visual size and symbol resolution. Further data on operator performance as a function of visual size is presented in Figures 86 and 87. Other sources cited by Banks et al. (1982) give the following (for capital letters), which are generally in accord with the previous values, but are perhaps slightly more conservative (see Table 18).

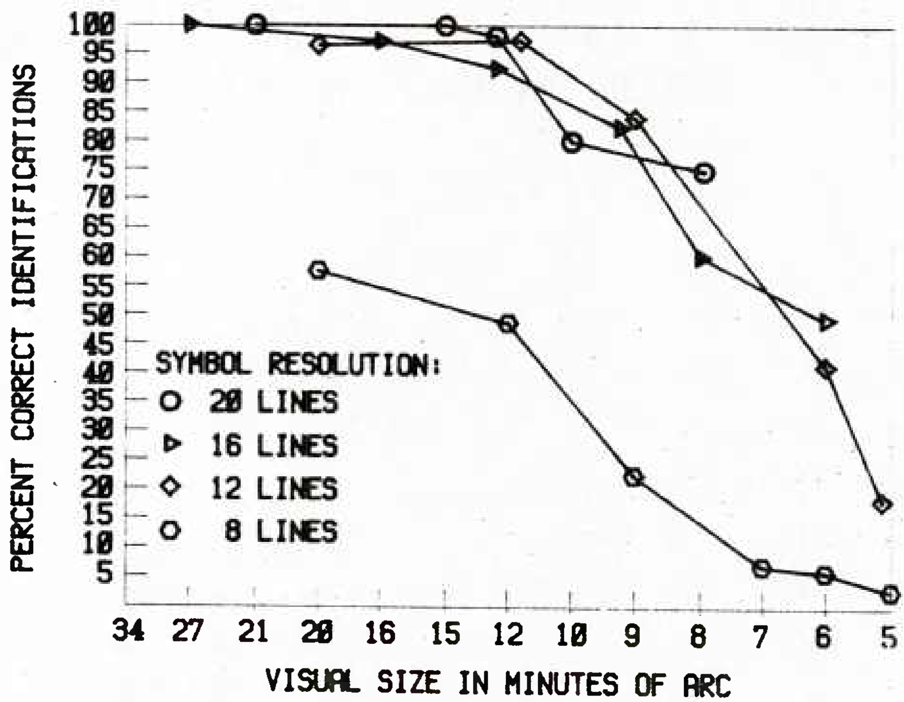


Figure 83. Accuracy of identification as a function of visual size and symbol resolution (Shurtleff, 1966b).

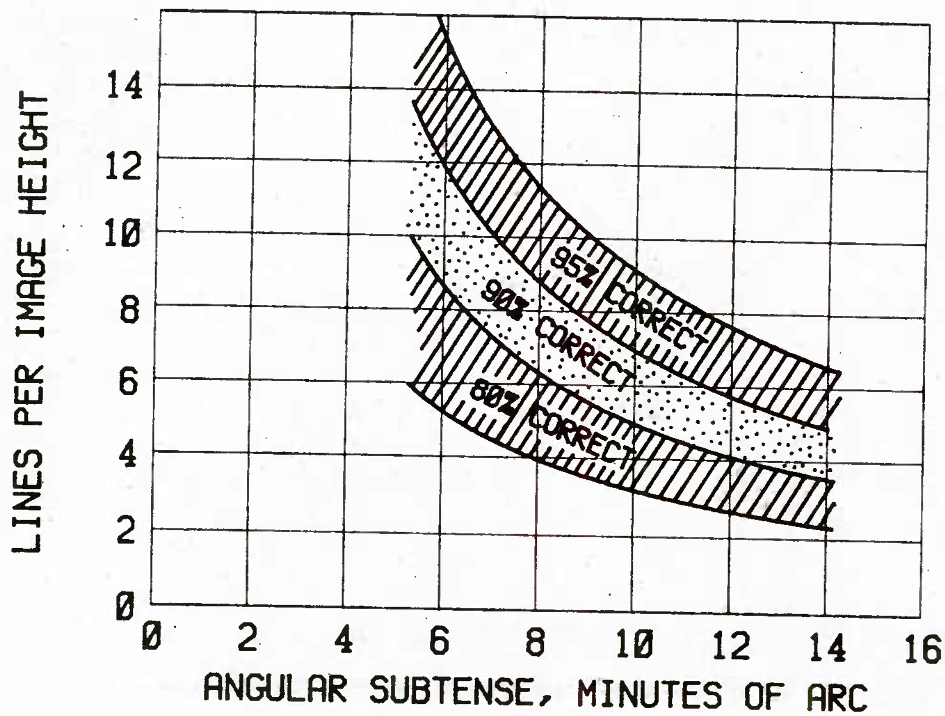


Figure 84. Tradeoff bands for angular subtense vs. line number for three levels of performance (Erickson, 1964).

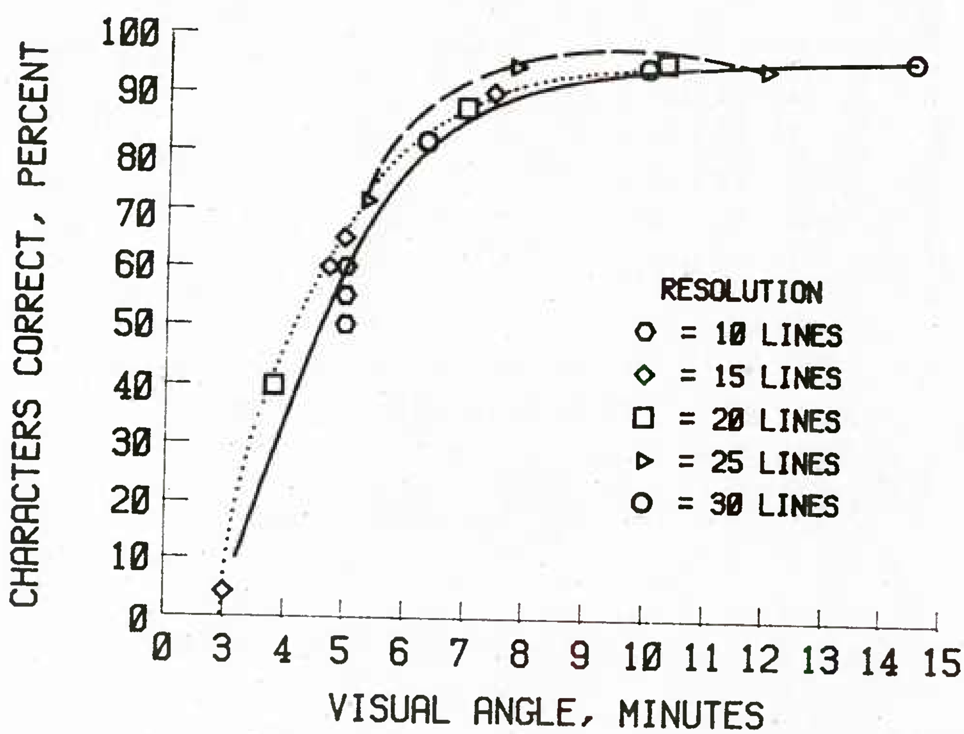


Figure 85. Relationship between visual angle and resolution.

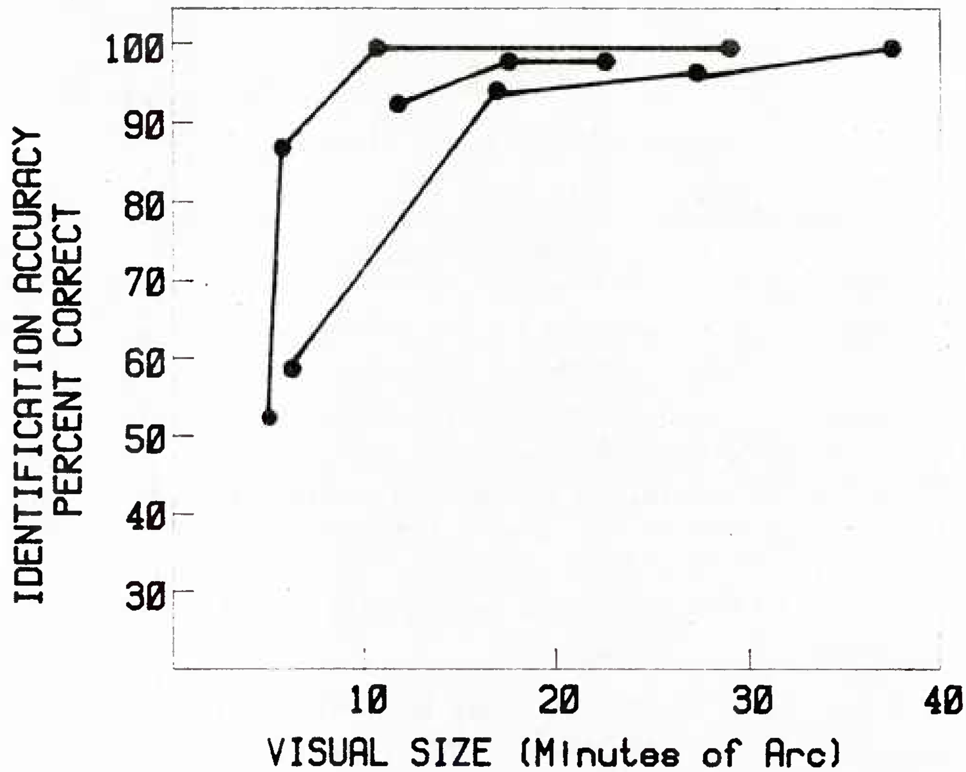


Figure 86. Relationship between symbol height and identification accuracy in three studies.

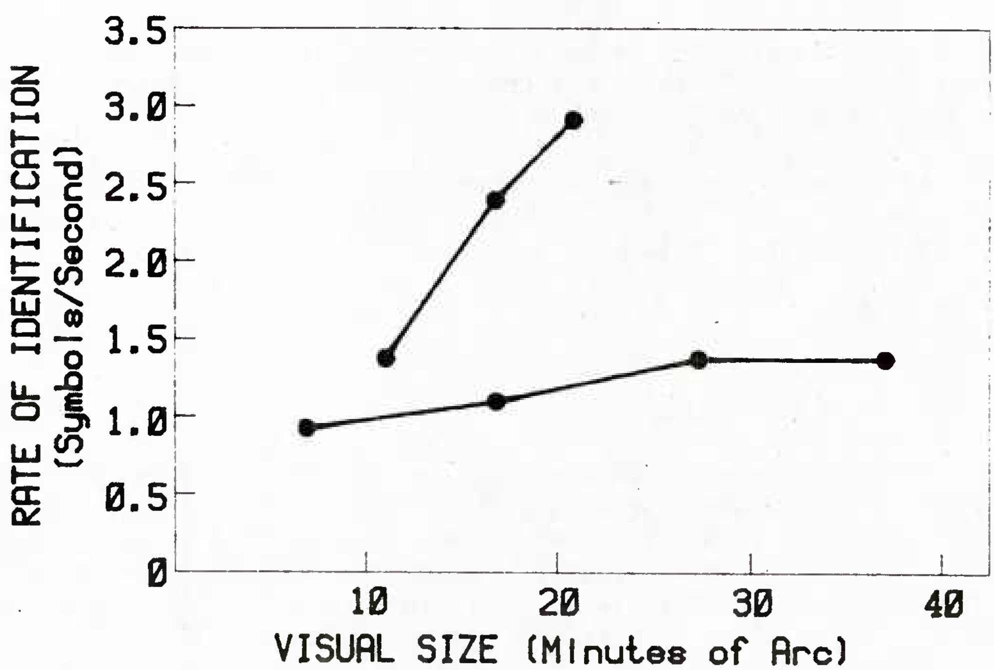


Figure 87. Relationship between visual size and identification rate.

Table 18

Recommended Symbol Size

Source	Recommendations
EG&G	Variable between 1.4 and 28 mm depending on viewing distance.
TUB	16 minutes of arc high, minimum; 20 minutes of arc high, preferred.
DIN	18 minutes of arc high for viewing distances greater than 50 cm; 2.6 mm high minimum for viewing distances less than 50 cm.
U of L	3.1 to 4.2 mm for a viewing distance of 70 cm.
DCIEM	3.5 mm minimum.
VDT	16 to 20 minutes of arc high, minimum; 3.1 to 4.2 mm minimum height, 3.0 mm minimum.
MILSTD	Variable between 2.3 and 29 mm depending on viewing distance.

Note from Figure 83 that all visual sizes above 12 minutes of arc give essentially the same performance for acceptable resolution.

However, as a general guide for system design, symbol size should be greater than 15 minutes of arc or 10 TV lines with good contrast or 21 to 25 minutes or 16 lines with poor contrast (Buckler, 1977).

The size of the display resolution element, in terms of its maximum dimension, and the maximum viewing distance D at which two adjacent elements can be discriminated is given by the formula

$$H = .003D, \tag{4.1}$$

where

H = character height.

The relationship between symbol height (expressed as visual size subtended by the height of the symbol at the observer's eye) and identification accuracy is shown in Figure 86 (Crook, Hanson, & Weisz, 1954b; Howell & Kraft, 1959; Seibert, Kasten, & Potter, 1959). Because of the interaction between visual size and other display parameters, the minimum acceptable visual size varies and is dependent upon the values of these other parameters. Two studies (Crook et al., 1954b, and Howell & Kraft, 1959) suggest that it is undesirable to select symbols whose height will subtend less than 15 minutes of arc at the observer's eye, while two other studies (Seibert et al., 1959; Shurtleff & Wuersch, 1979) indicate that high accuracy can be achieved with symbols whose height subtend an angle as small at 10 minutes of arc at the observer's eye.

The relationship between visual size and rate of identification shown in Figure 87 reinforces the conclusions displayed in Figure 88.

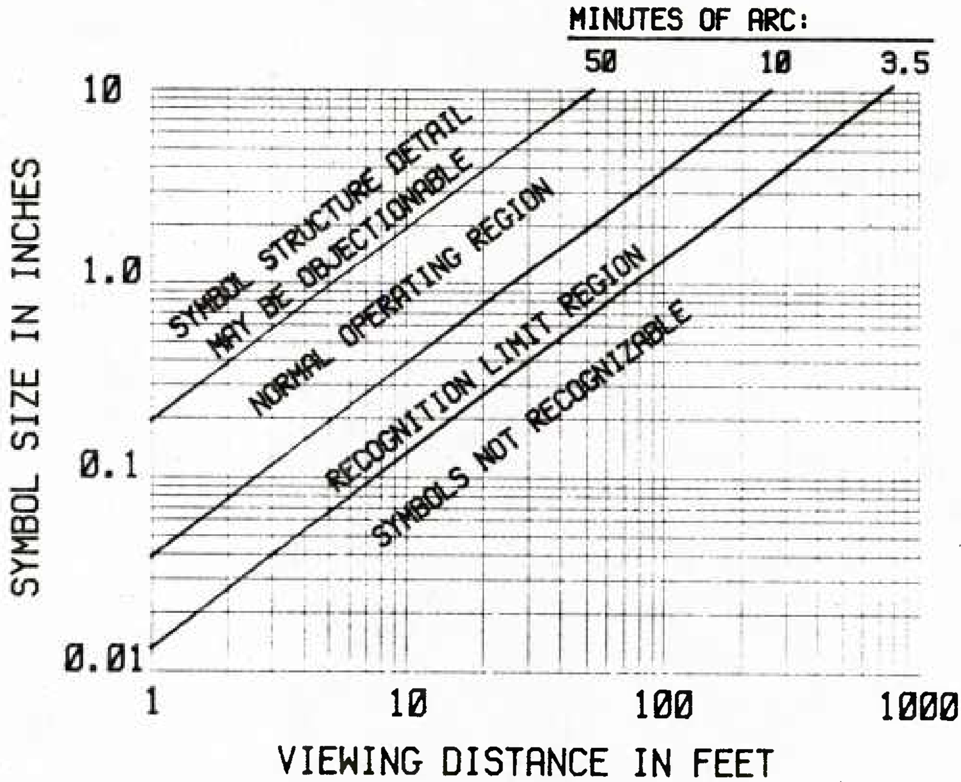


Figure 88. Relation of symbol resolution to viewing distance (Whitham, 1965).

Where the display format is comprised largely of symbology, the relationship of symbol size to screen height is shown in Figure 88. Symbols three to five times the minimum size of 10 minutes of arc are usually acceptable, but will degrade the maximum display data capability.

It is also possible to determine maximum element size from the number of vertical elements or raster lines and the display screen height (see Figure 89). Example: For 500 line TV screen with a height of 15 inches, the maximum element size is 25 mils, which is consistent with the spot size of normal TV CRTs.

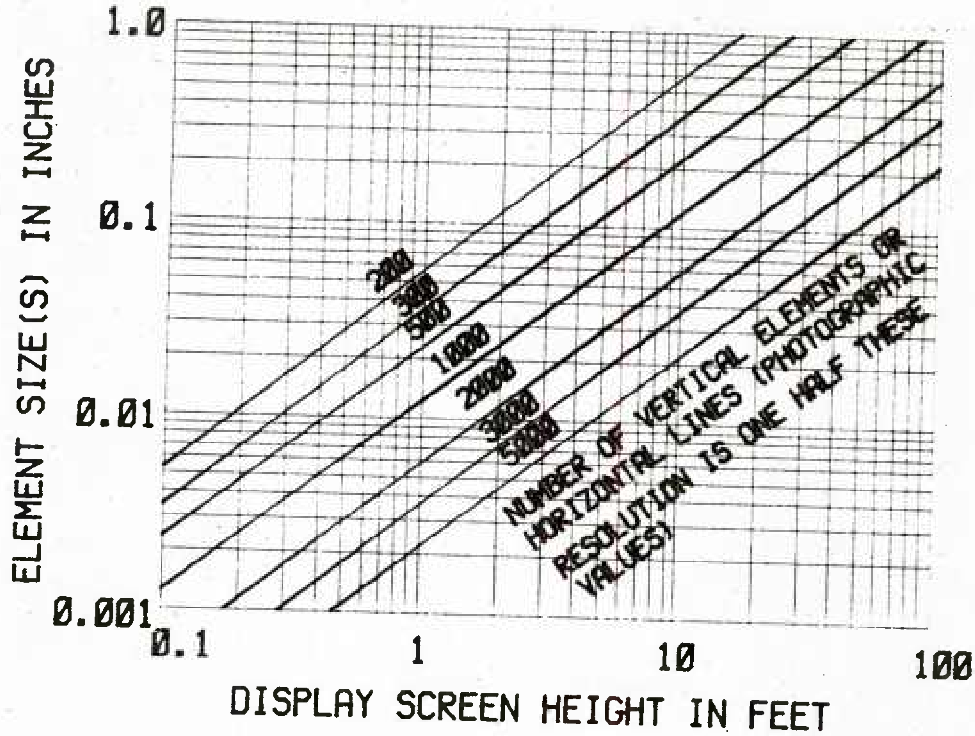


Figure 89. Relation of screen height to element size and number of vertical elements or horizontal lines (Whitham, 1965).

4.4 How to Determine the Number of Symbols That Can Be Presented

The number N of characters of limiting resolution that can be accommodated in a square screen having a side dimension S is given by the equation:

$$N = \frac{D}{S}^{-2} \times 10^5, \tag{4.2}$$

where D = the viewing distance and S = screen size.

If character height visually subtends 10 minutes of arc for limited conditions, then the total symbol area will subtend 7.5 by 15 minutes of arc.

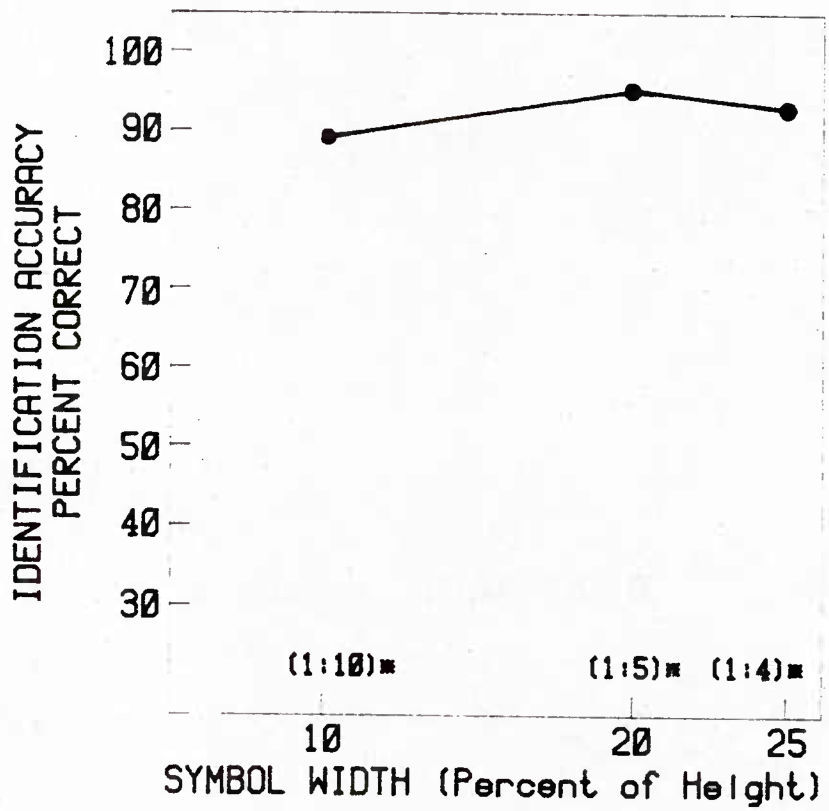
If square adjacent symbols that visually subtend 10 minutes of arc for each side are used, the maximum number is given by the equation:

$$N = \frac{D}{S}^{-2} \times 1.1 \times 10^5. \tag{4.3}$$

Practical limits for the value of D/S normally lie in the range between 1 and 5. The maximum symbol populations are between 4×10^3 and 10^5 for normal values of D/S.

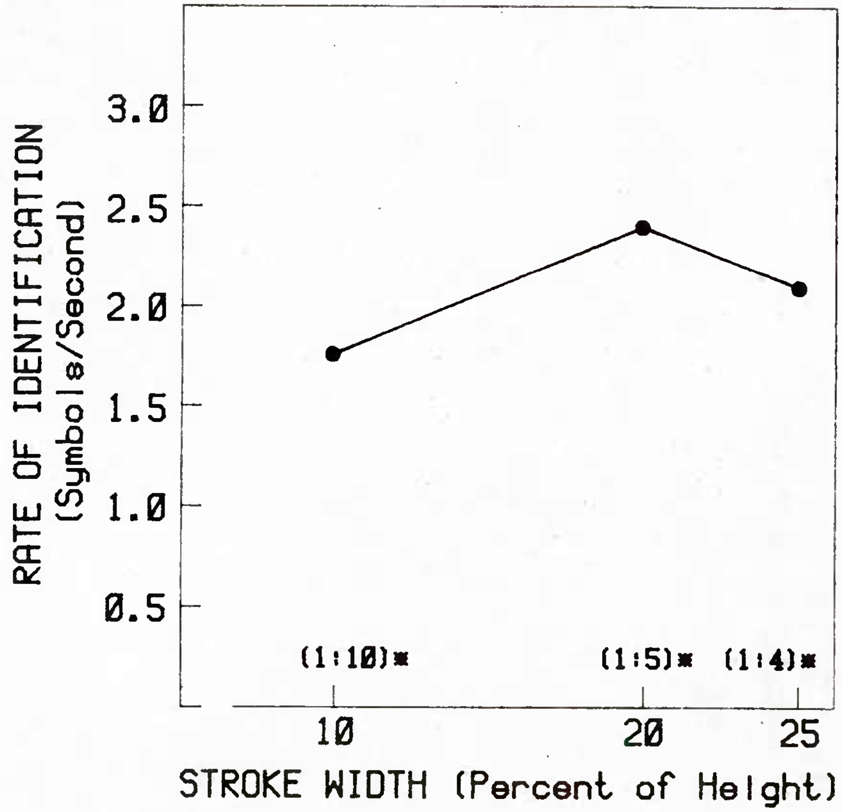
4.5 Stroke Width-to-Height Ratio

Rate and accuracy of identification as a function of symbol stroke width are shown in Figures 90 and 91. For each, the best stroke width is 10 percent of symbol height corresponding to a stroke-width-to-height ratio of 1:5 (Crook, Hanson, & Weisz, 1954a).



*Stroke width-to-height ratio.

Figure 90. Relationship between stroke-width and identification accuracy.



*Stroke-width-to-height Ratio.

Figure 91. Relationship between stroke width and rate of identification.

4.6 Luminance

Although a luminance contrast ratio of 10:1 has become the generally accepted industrial standard for display design, the experimental data are not very consistent with each other, perhaps because the studies were not carried out in the same way. The results of three studies (Howell & Kraft, 1959; Crook et al., 1954b; Shurtleff & Wuersch, 1979) are shown in Figures 92 and 93. One complication is that the acceptable minimum ratio depends on a number of factors: absolute luminance levels, symbol size, and symbol blur. Shurtleff (1980) recommends that the minimum acceptable contrast ratio for general display conditions be in the range of 10:1 to 18:1.

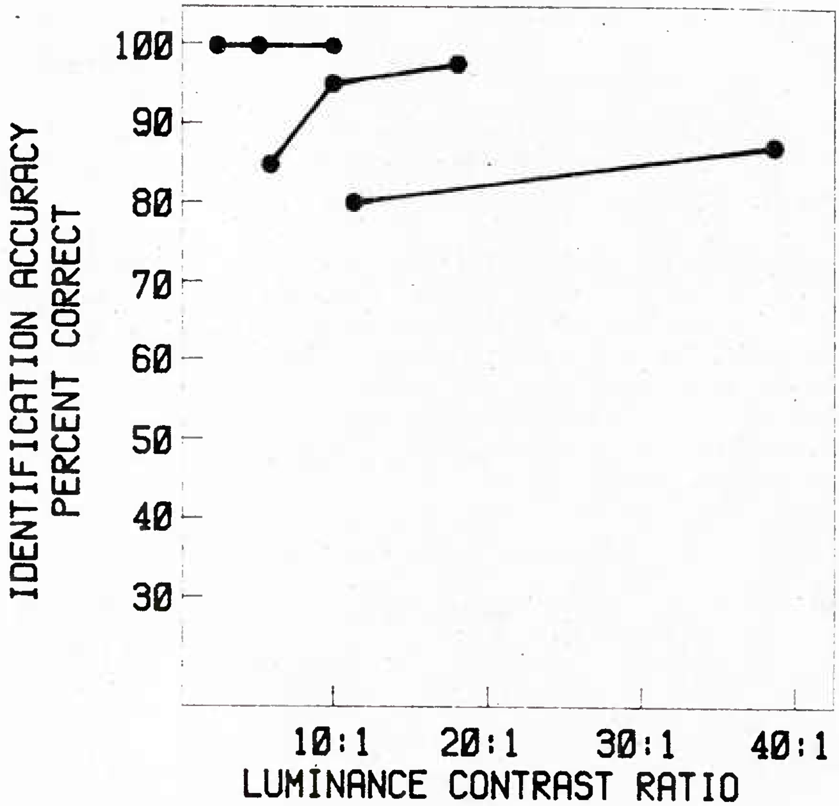


Figure 92. Relationship between luminance contrast ratio and identification accuracy.

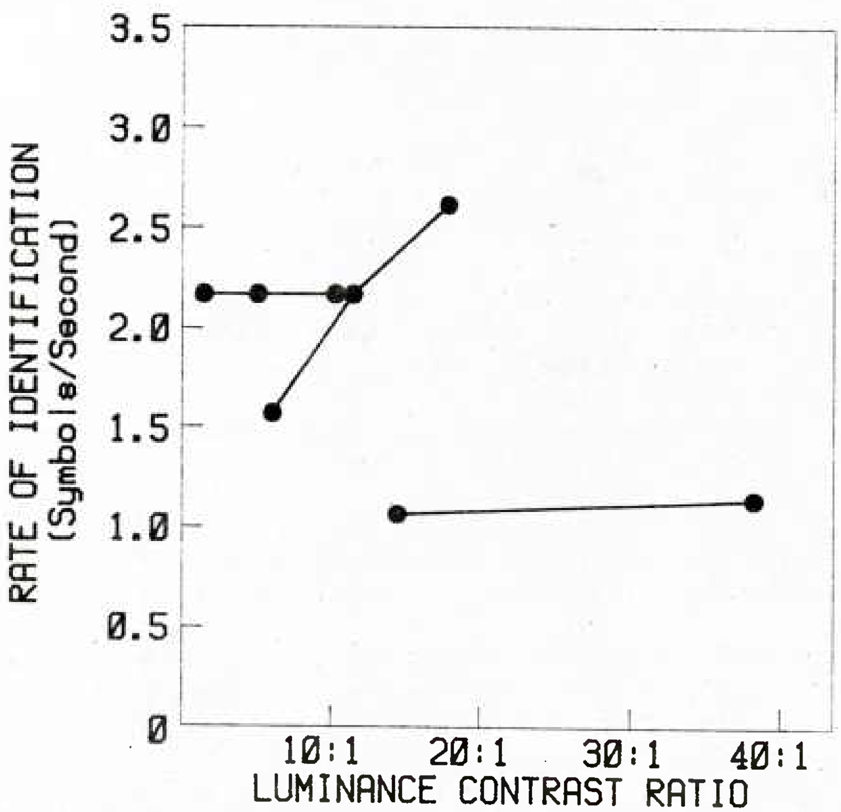


Figure 93. Relationship between luminance contrast ratio and rate of identification.

Under certain conditions, contrast ratios as low as 2:1 can be used. Acceptable contrast ratios assume that the general surround/ambient matches or varies by only 1/3 of that for the symbol or background, whichever is brighter.

The studies described in Figure 94 (Crook et al., 1954b; Shurtleff, Botha & Young, 1966; Faulkner & Murphy, 1973) suggest that luminances below 10 fL should be avoided because of potential adverse effects on identification accuracy and that little gain in performance will occur with increases in luminance beyond 10 to 20 fL. Threshold acuity does not change very much with increases in luminance from 10 to 1000 ft. L (Faulkner & Murphy, 1973). It is reasonable to assume that the relationship for symbol identification would be similar to that for acuity, since acuity is commonly measured by using letter forms on Snellen charts.

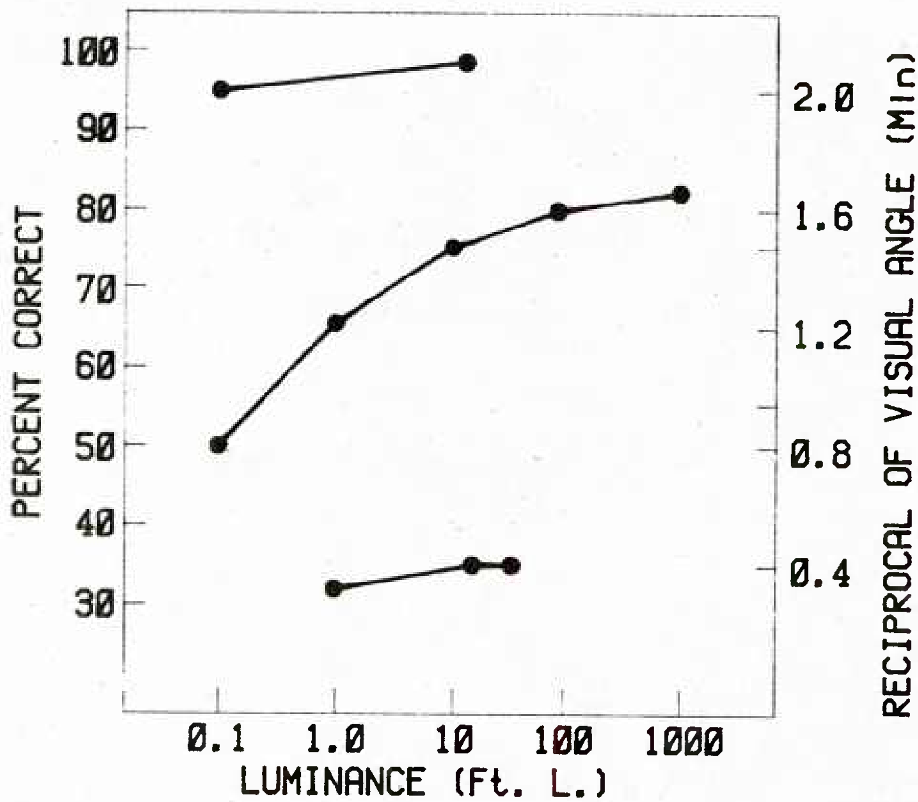


Figure 94. Relationships between symbol luminance, threshold acuity and identification accuracy.

Display design should have a minimum brightness of 10 fL. For most applications, it is probably not necessary for the maximum brightness to exceed 20 fL.

Complicated interactions exist among contrast ratio, absolute luminance, and visual size. The data suggest that the minimum acceptable contrast ratio can be as low as 2:1 when absolute luminance is 10 fL or greater and visual size is 10 minutes of arc or greater. However, when absolute luminance is low (in the range of .01 to .1 fL), the minimum contrast ratio can only be as low as 5:1 if the visual size is 10 minutes of arc or greater. For symbol sizes smaller than 20 minutes of arc, the minimum contrast ratio

must be increased to 18:1 (and possibly greater for symbol sizes below 10 minutes of arc), if a high level of identification performance is to be achieved. It is important to note that equal contrast ratios do not yield equal legibility. Absolute luminance and visual size of symbols have to be considered along with equal contrast ratios.

Figures 95 and 96 suggest that, for both identification accuracy and speed at high contrast (18:1), a wide range of stroke-width-to-height ratio selections (1:10 to 1:4) are possible. At low contrast (5:1), the choice of stroke width is more critical, with preferred values in the middle range of 1:5 to 1:6 (Crook et al., 1954b).

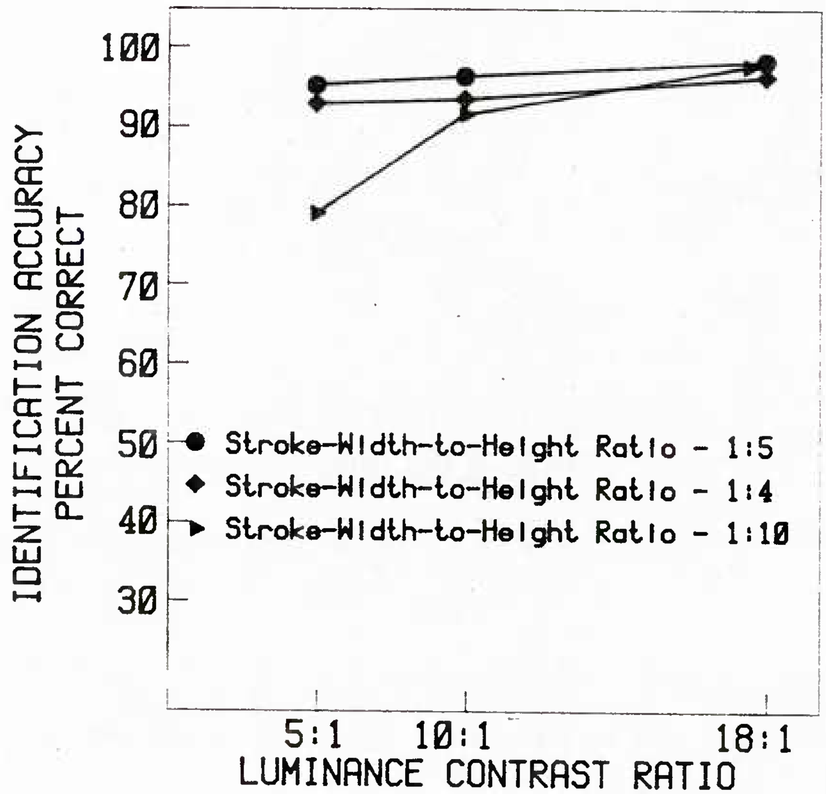


Figure 95. Relationships among luminance contrast ratio, stroke width, and identification accuracy.

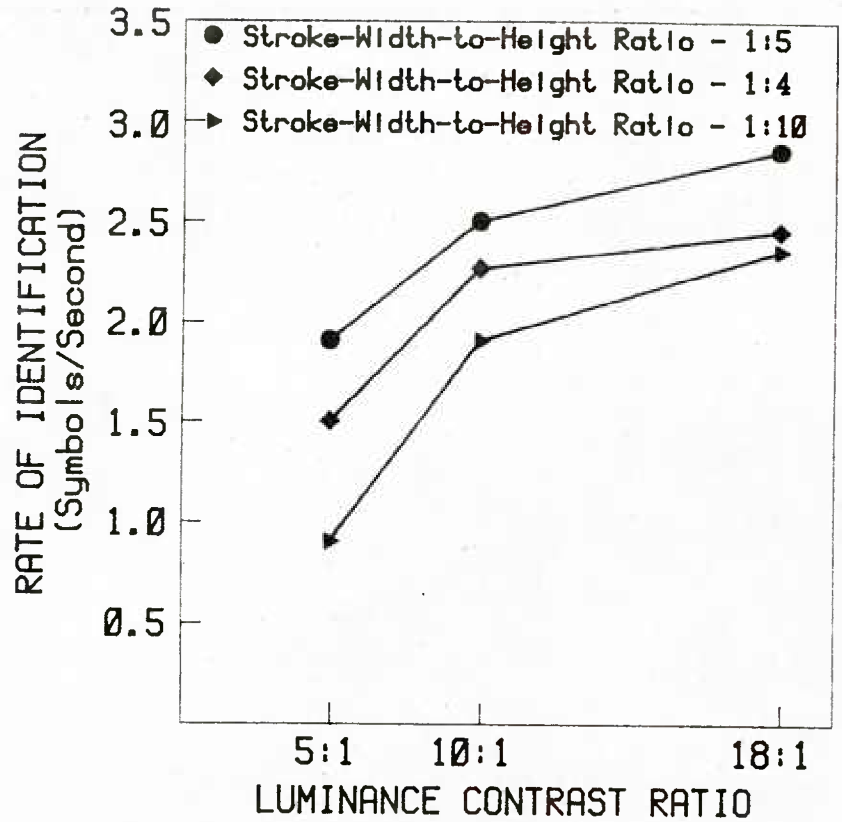


Figure 96. Relationships among luminance contrast ratio, stroke width, and rate of identification.

The minimum acceptable contrast ratio is a function of the absolute luminance level and the visual size of the symbols. If, however, the designer provides a contrast of at least 18:1, wide variations in stroke width and symbol height are possible over a range of luminances from .1 to 50 fL.

Visual size subtended by symbol height needed for high accuracy and speed of identification depends upon absolute symbol luminance. For low values of absolute luminance (.01 to .1 fL), a minimum visual size of 20 minutes of arc is recommended by Shurtleff (1980); for intermediate values of absolute luminance (10 to 50 fL), a minimum visual size of 10 minutes of arc is recommended. A stroke-width-to-height ratio of 1:5 and a symbol width of 75 percent of symbol height are recommended for displays.

Visual size and symbol width and stroke width also interact. Figures 97 and 98 show that, at a luminance of 12 fL, neither symbol width nor stroke width has a negative effect on performance (Crook et al., 1954a). Symbol width and stroke width variations at low luminance have some effect on accuracy and rate of identification. Effects are more pronounced for rate.

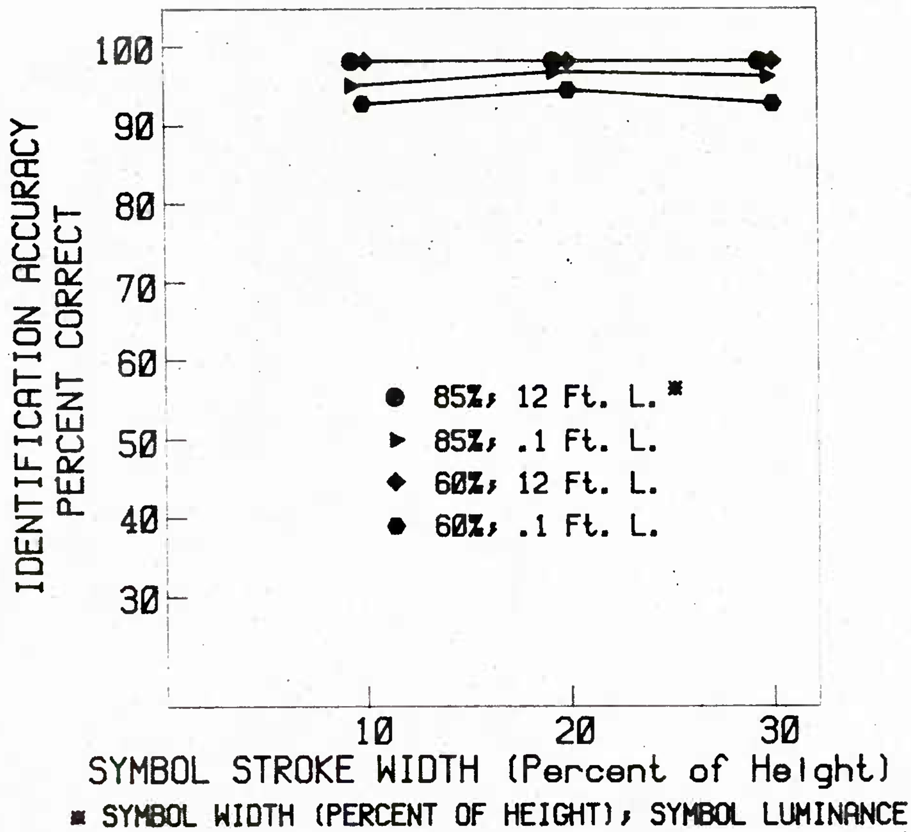


Figure 97. Relationships among symbol stroke width, symbol width, symbol luminance, and identification accuracy.

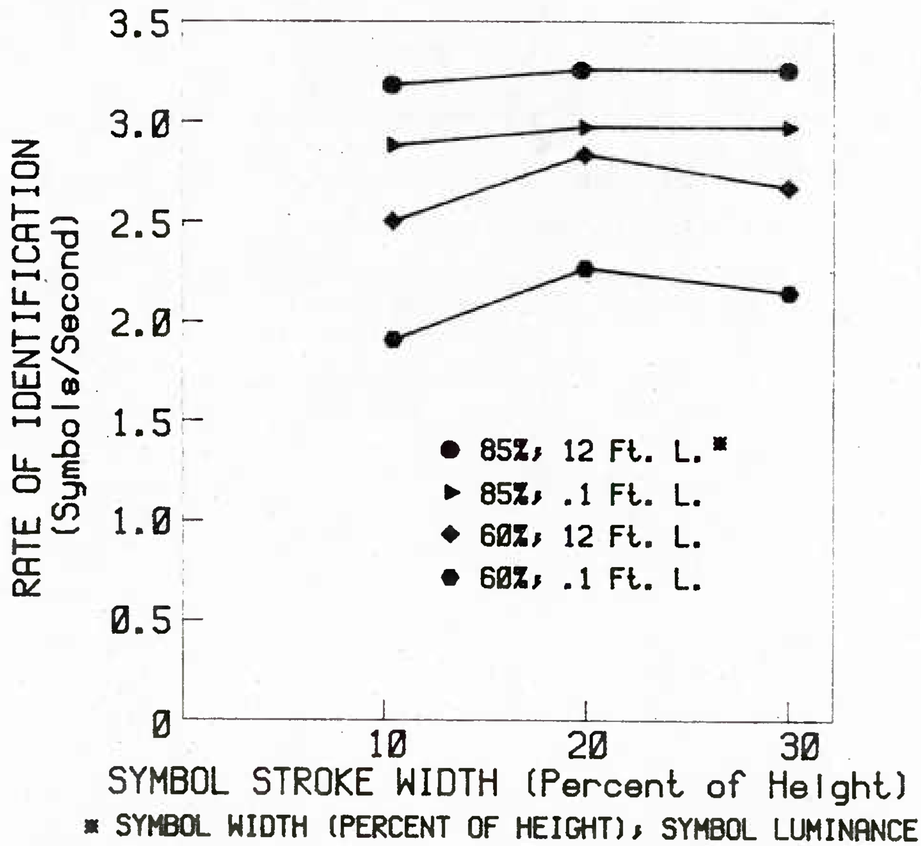


Figure 98. Relationships among symbol stroke width, symbol width, symbol luminance, and rate of identification.

Figures 99 and 100 show the relationships between symbol stroke width and symbol height expressed in visual size (minutes of arc) and identification accuracy and rate; these relationships are similar to previous ones. For the largest size symbols, just about any stroke width will do. For the smaller symbols, intermediate stroke widths appear to be the best choice (Crook et al., 1954b).

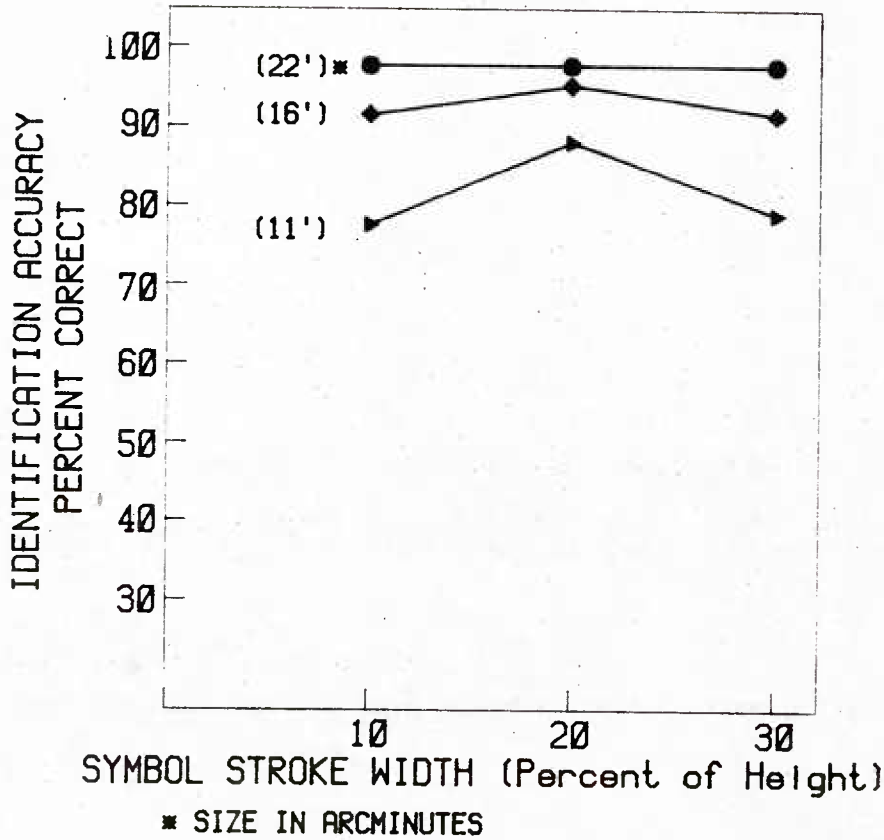
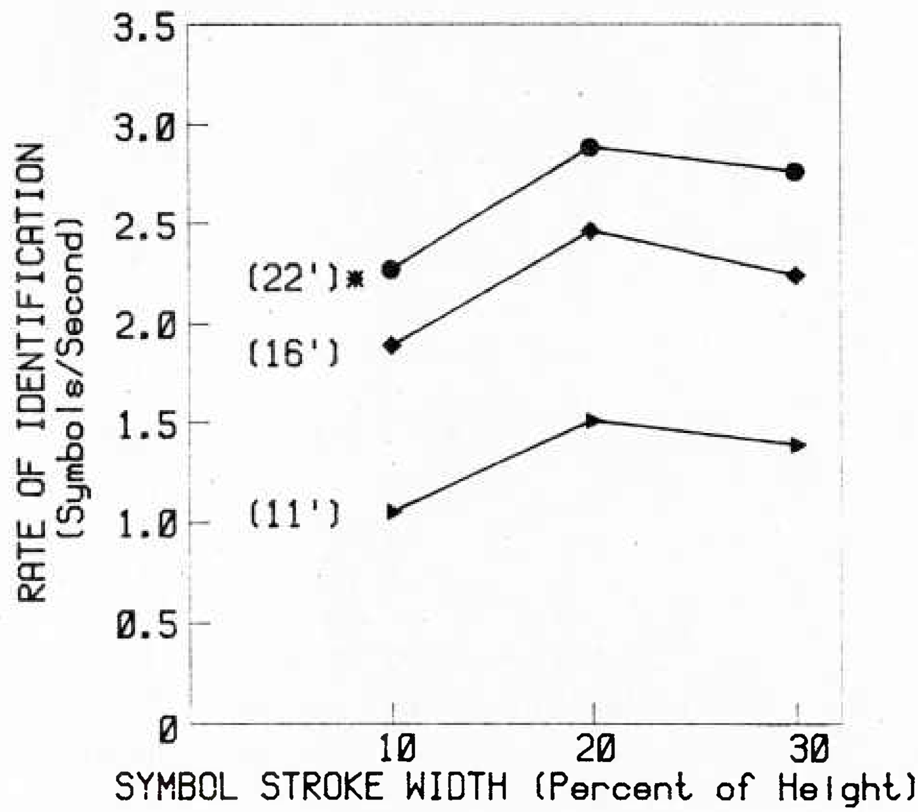


Figure 99. Relationships among symbol stroke width, visual size, and identification accuracy.



*Size in arc minutes.

Figure 100. Relationships among symbol stroke width, visual size, and rate of identification.

4.7 Symbol Spacing

Horizontal space between characters is related to identification accuracy and rate. Figures 101 and 102 (Crook et al., 1954b; Shurtleff & Alexander, 1972) suggest that spacing can be as close as 10 to 15 percent of symbol height (measured between adjacent outer boundaries of symbols) with no loss of identification accuracy or speed. (Unlabelled curves in these and subsequent figures represent the studies cited.) Spacing between letters in normal typewritten copy averages between 8 and 10 percent of symbol height. Therefore, average typewritten spacing of 10 percent of symbol height would be adequate for many displays. For dot matrix symbols generated on CRTs, the minimum can be one dot spacing for symbols made up in traditional 5 x 7 and 7 x 9 matrices. The design criterion for direct-on-line viewing is that horizontal spacing can be as close as 8 to 10 percent of symbol height. For off-axis viewing of 45 degrees or more, horizontal spacing should be increased 25 to 50 percent of symbol height.

If nonoptimal display conditions are anticipated, horizontal spacing should be no closer than 25 percent of symbol height. This spacing corresponds approximately to that provided by two dot elements for symbols generated in traditional 5 x 7 and 7 x 9 matrices. If display conditions are optimal, horizontal spacing can be as close as 8 to 10 percent of symbol height, approximating a one-dot-element spacing for 5 x 7 and 7 x 9 dot matrices.

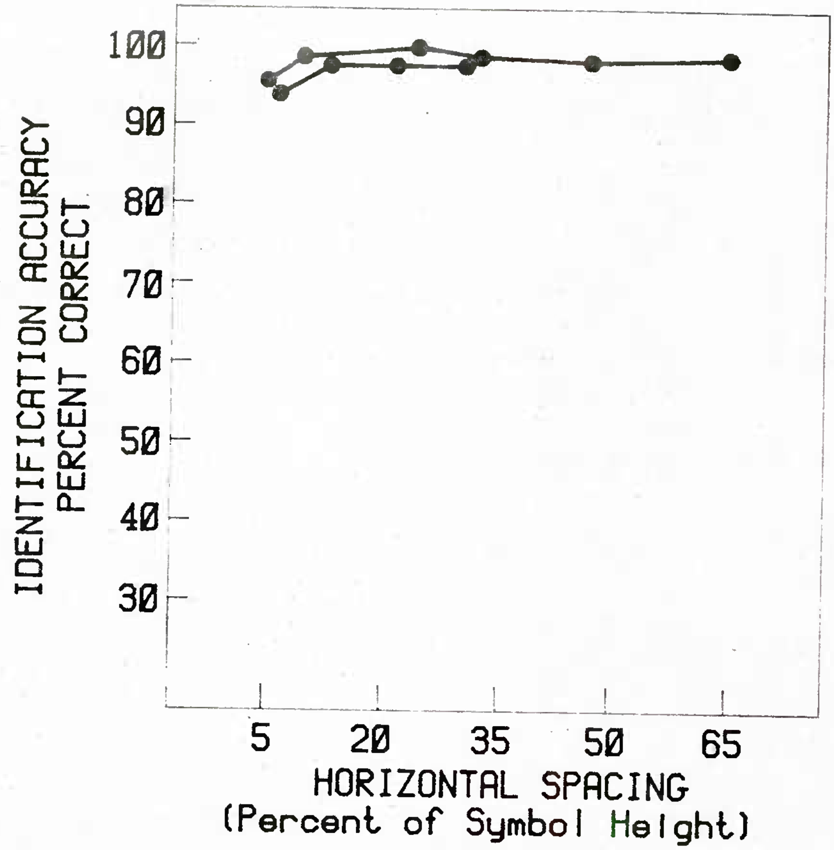


Figure 101. Relationship between horizontal spacing and identification accuracy.

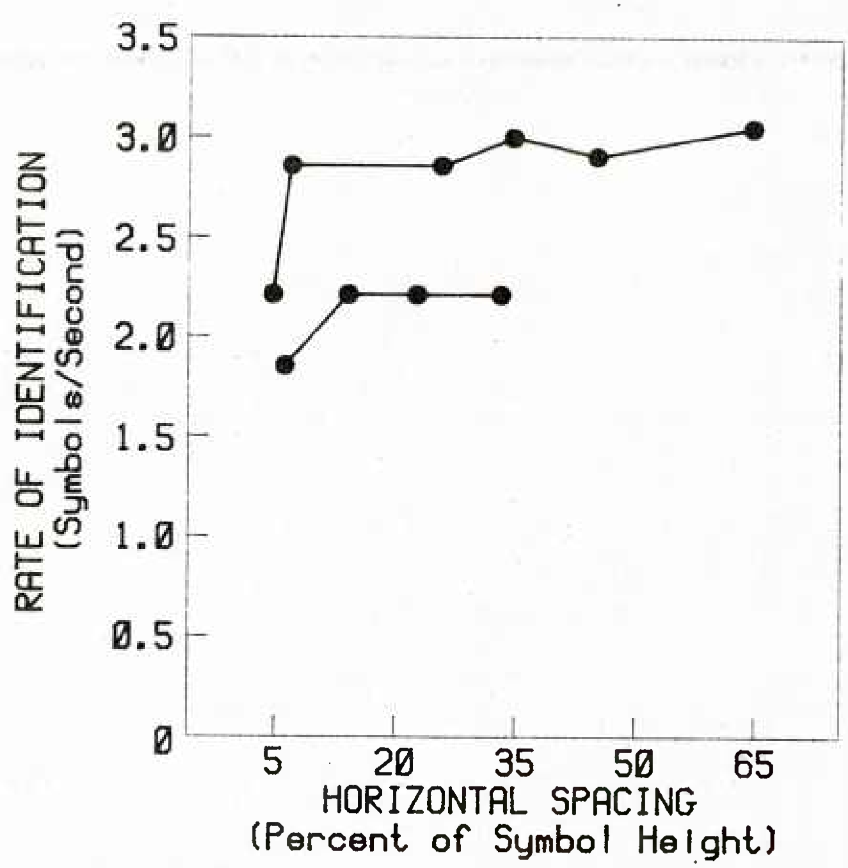


Figure 102. Relationship between horizontal spacing and rate of identification.

4.8 Geometric Distortion

The combined effects of all geometric distortion should not displace any point on the projected display from its correct position by more than 2 to 5 percent of picture height.

The projector should be capable of correcting keystone or trapezoidal distortion within a range of ± 15 degrees off center.

DIN recommends that barreling or pin cushioning of the image should not exceed 2 percent of the image width at the top and bottom edges of the screen or 2 percent of image height for the side edges of the screen display area. Character size should not vary more than 10 percent in either the horizontal or vertical direction ((max - min)/max x 100). Image or character jitter should not exceed .05 percent of the screen diagonal.

4.9 Bandwidth

An important factor that affects symbol legibility is video bandwidth. Clauer, (1967) and Seibert (1964) investigated the effects of bandwidth on symbol legibility for analog, closed circuit TV systems. The results of the two studies, shown in Figure 103, indicate that bandwidths below 2.0 MHz impair identification accuracy.

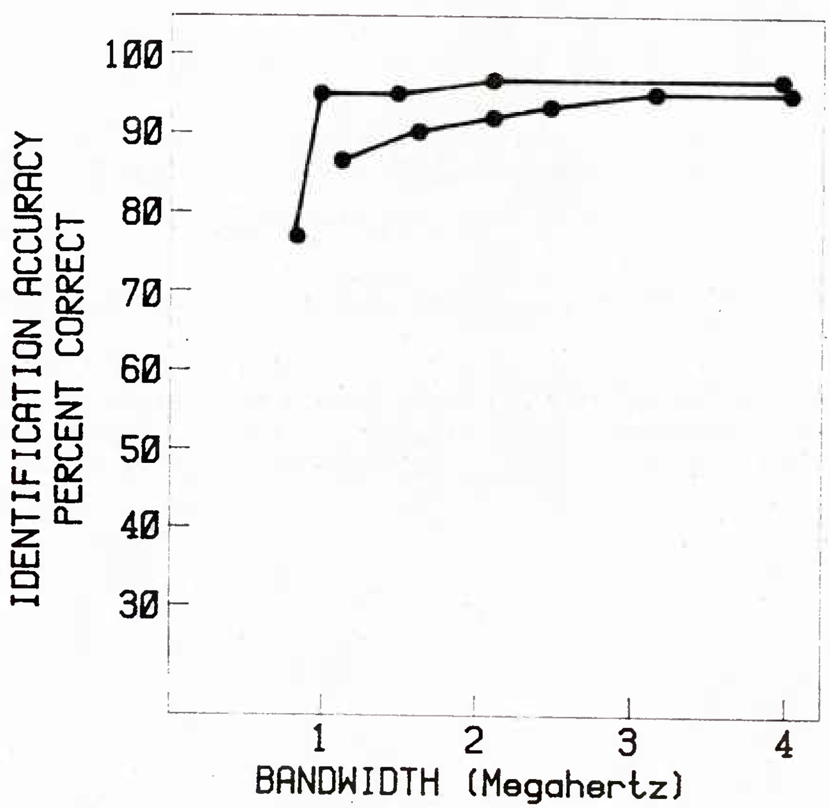


Figure 103. Relationship between video bandwidth and identification accuracy.

Additional confirmation is given by the study by Shurtleff (1966a) shown in Figure 104. Since it is common practice to provide TV systems with bandwidths of 4 to 5 MHz or greater, the minimum required for high identification accuracy is well below current standards. As long as the visual size of the alphanumeric is 10 minutes of arc or more, there appears to be no appreciable loss in identification accuracy as a function of reducing video bandwidth, within the range 4.0 to 1.0 MHz.

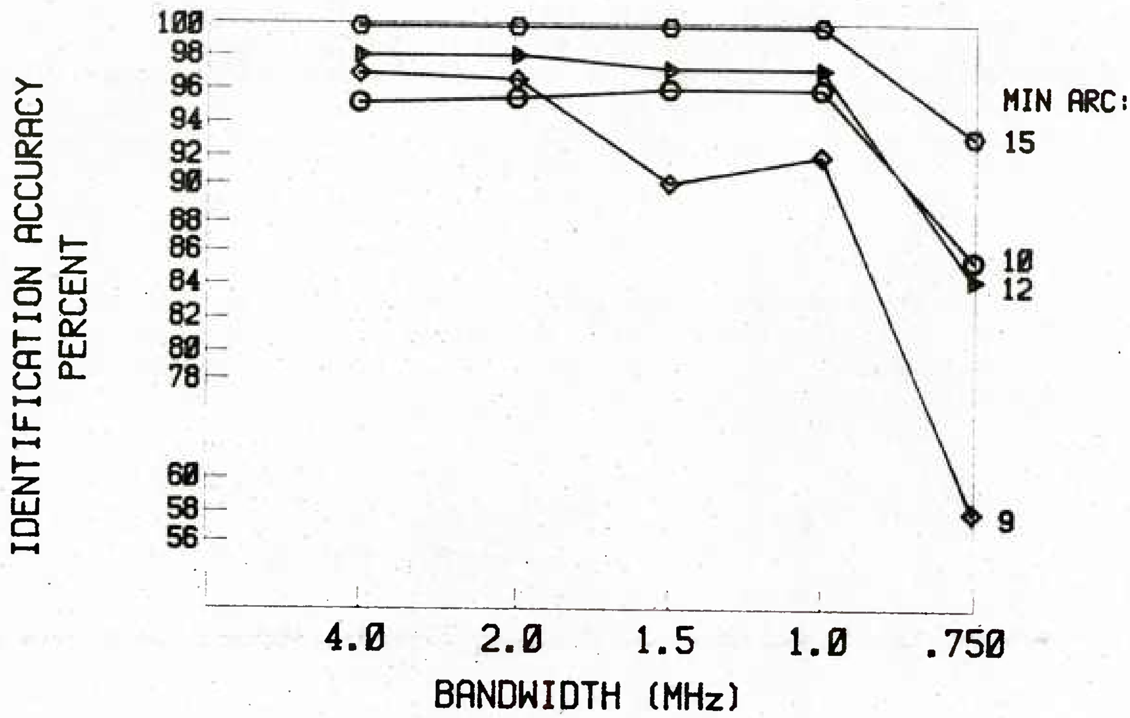


Figure 104. Effect of bandwidth on identification accuracy.

The type of symbol is important here. For nonmeaningful symbols (e.g., Landolt rings), the reduction in bandwidth from 8 MHz to 2 or 1 MHz is much more pronounced. Tables 19 and 20 describe the percentage of target identification accuracy lost.

Table 19

Effects of Video Signal Bandwidth on Target Identification Ability (Shanahan, 1964)

Video Signal Bandwidth (MHz)	Target Contrast Ratio		
	100%	81%	27%
8 to 2	23%	24%	15%
8 to 1	54%	52%	42%

Table 20

Effects of Target Contrast Ratio on Target Identification Velocity (Shanahan, 1964)

Target Contrast Ratio (Percent)	Video Signal Bandwidth (MHz)		
	8	2	1
100 to 81	7.4%	7.9%	3.8%
100 to 27	26.0%	18.0%	6.6%

The studies by Clauer (1967) and Seibert (1964) also suggest that the adverse effects of video bandwidth reduction below 2 MHz can be offset by the use of high values of scan lines of 17 lines per symbol height. Clauer (1967) provides criteria and procedures for determining minimum bandwidth requirements for analog closed-circuit TV systems when both the copy to be televised and the legibility are specified.

For digital TV, in which symbols are constructed by a symbol generator rather than from input from a TV camera, bandwidth requirements can be calculated by use of the following formula (Shurtleff, 1980):

$$f = .712\, pn^2N, \tag{4.4}$$

where f = bandwidth,

p = aspect ratio of scanning lines,

n = the number of lines needed to meet symbol capacity requirements (e.g., 24 lines of 7 x 9 dot symbols would require 9 lines for the symbol plus 3 lines for spacing multiplied by 24 lines of text equalling 288 lines),

N = frame rate.

4.10 Viewing Distance

If average viewing distance from the console is assumed to be 18 inches, the minimum element size would be .15 inch. Figure 105 can be used to determine optimum element size as a function of viewing distance. The relationship among size of display screen, acceptable viewing distance, and amount of detail or number of characters that can be displayed is shown below. For a given viewing distance, display size must be increased if the amount of detail displayed is to be increased. The effect of viewing distance upon response time to symbols in dot matrix form is shown in Figure 106 (Synder & Maddox, 1978). They found that the effects of viewing distance account for large percentages of the variation in responses. Over 40 percent of the variation in accuracy was attributable to viewing distance; over 20 percent, for response time.

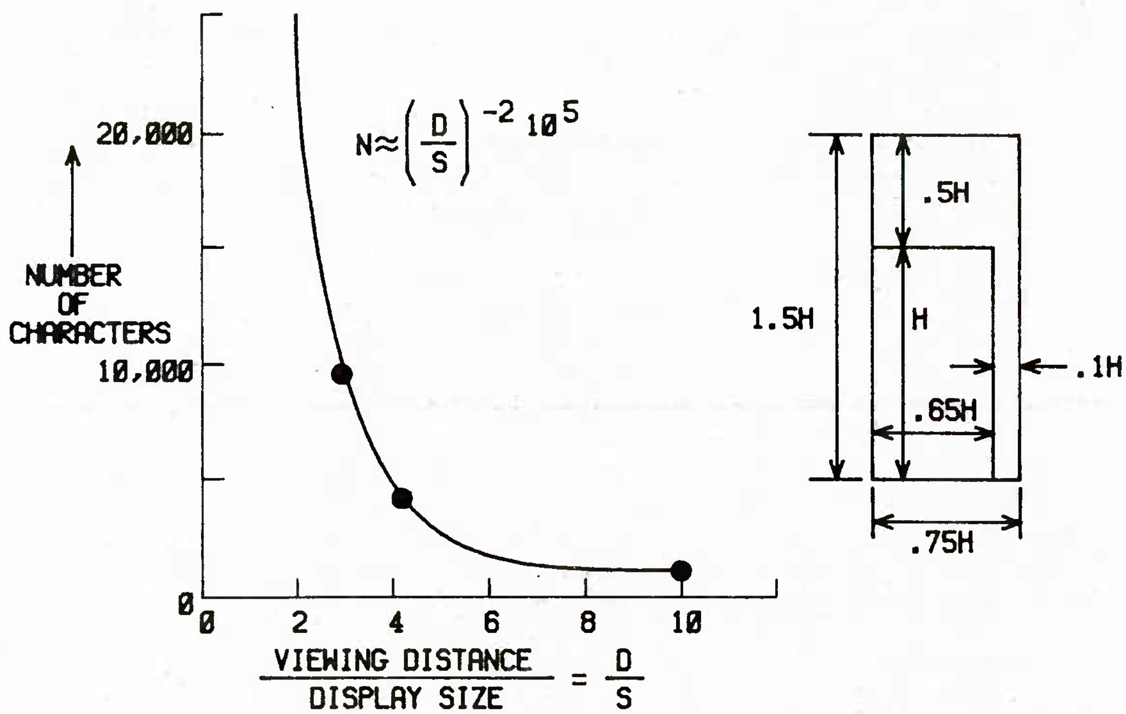


Figure 105. Relationship between display detail, display size, and viewing distance (Whitham, 1965).

Conditions:

1. Square Display
2. Character slot at shown
3. Character height H subtends 10 min. of arc at viewing distance, D, (M=.0030)
4. Increased viewing distance at display edges is neglected
5. Adequate brightness and contrast exist
6. Viewing distance D is greater than 13 inches
7. No margin allowed at display edge

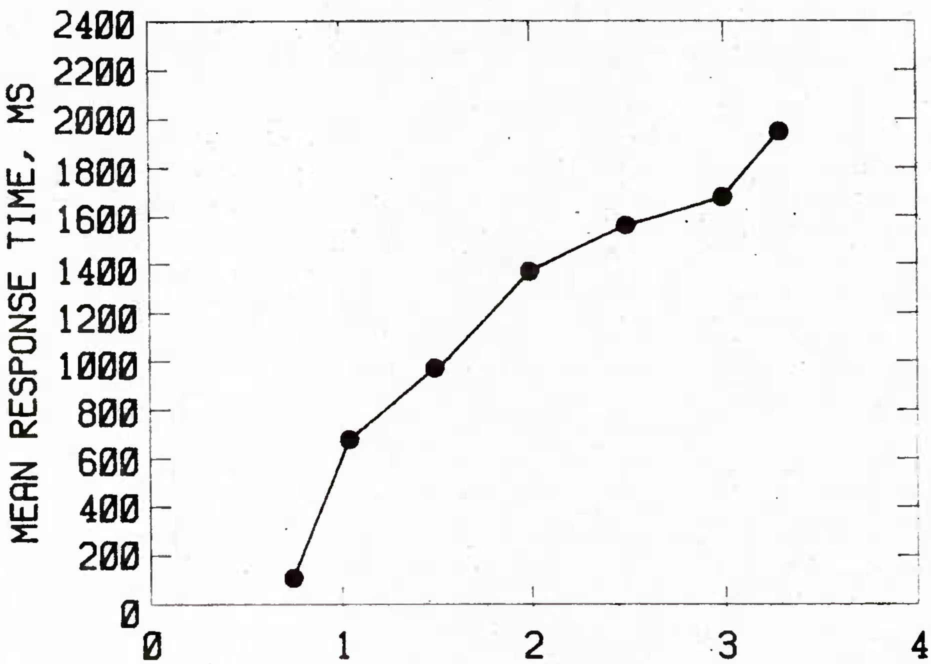


Figure 106. Effect of viewing distance upon response time.

4.11 Direction of Scanning

The orientation of TV scan lines is normally parallel to the base of the symbols. Clauer (1967) compared two directions of scanning--one with the raster lines in a plane horizontal to the base of the letter (normal orientation) and a second with the raster lines rotated 90 degrees so that they are in a plane vertical to the base of the symbol.

For all levels of linear resolutions and bandwidth, accuracy of symbol identification was better when the raster orientation was horizontal to the base of the symbols rather than vertical to the base of the symbols. These differences were more pronounced at the lower bandwidths--1 to 2 MHz--(7% difference) than at the higher bandwidths--3 to 5 MHz--(1% to 2% difference).

Using a TV scan-line simulation technique, Shurtleff, Botha, and Young (1963) investigated angular scan line orientations of 0, 45, and 90 degrees with respect to the base of the symbols. Although the data must be interpreted with caution because the study used simulated rather than live TV, the results showed that scan-line orientation had no statistically significant effect on either symbol identification accuracy or speed. Symbol identification accuracy and speed were consistently, but only slightly, better when the scan lines were oriented 45 degrees to the base of the symbols than in either of the other two orientations of 0 and 90 degrees.

4.12 Symbol Characteristics

Table 21 presents the recommended character heights for alphanumerics as a function of viewing distance.

Table 21

Recommended Minimum Alphanumeric Character Heights as a Fraction of Viewing Distance

Type of Displayed Information	High Display Brightness (Down to 1.0 fL)	Low Display Brightness (Down to .03 fL)
Critical data, position on display variable	.0045 to .007	.007 to .011
Critical data, position fixed	.0035 to .007	.0055 to .011
Noncritical data (labels, etc.)	.002 to .007	.002 to .007

The optimum size of letters and numerals on CRT displays is a function of viewing distance, illumination, and movement of numerals. Figure 107 shows these relationships with data based on conventionally printed displays not CRTs. Considering 18 inches as the typical viewing distance, CRT letters should be from about .08 inches to .28 inches (Barmack et al., 1966).

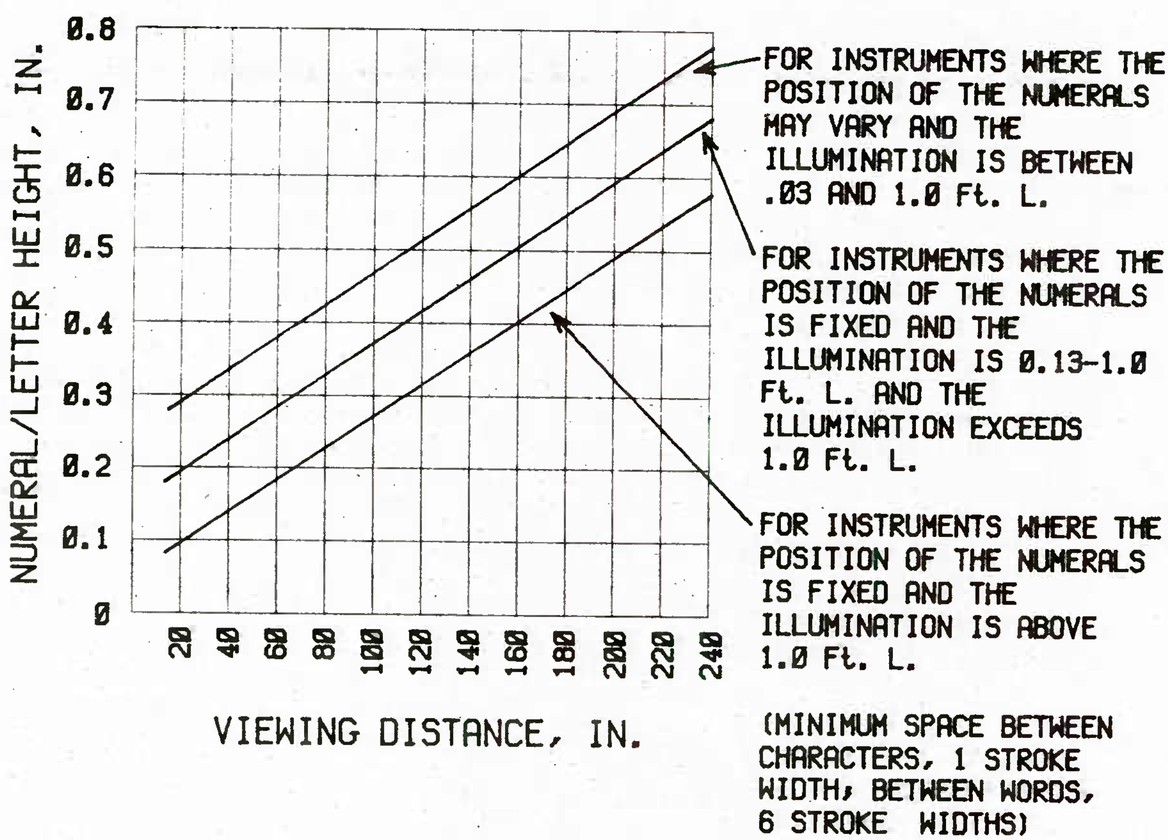


Figure 107. Letter height versus viewing distance and illumination level (Barmack et al., 1966).

Observers most commonly confuse the following alphanumerics (Kinney, 1965):

Mutual	One-Way
O and Q	C called G
T and Y	D called B
S and 5	H called M or N
I and L	J, T called I
X and K	K called R
I and 1[a]	2 called Z[a]
	B called R, S, or 8[a]

[a]These three often comprise 50 percent or more of the total confusions.

It is possible to use as few as seven lines per word height and still retain 98 percent accuracy of word identification as shown by Table 22.

Table 22

Identification Accuracy of Common Five-letter Words as a Function of Resolution

Resolution			
Solid Stroke	10 lines	7 lines	5 lines
100%	99%	98%	97%

4.13 <u>Aspect Ratio</u>

Aspect ratios of 5:7 or 2:3 (width to height) are recommended for greatest legibility. Stroke width should be in the range of 1/6 to 1/10 character height with the thinner widths used for illuminated characters on a dark background (Poole, 1966). A wide stroke width should be used for lower symbol resolution (Shurtleff, 1966b).

4.14 <u>Variations in TV Quality</u>

At resolutions of 8, 10, and 12 lines, quality of TV equipment appears to have no significant effect on accuracy and speed of identification of standard Leroy symbols (most commonly employed alphanumeric). At 6 lines, identification is superior for better quality TV (945 lines). Even high quality TV required a minimal resolution of 10 lines (Shurtleff, 1966a). See Figure 108.

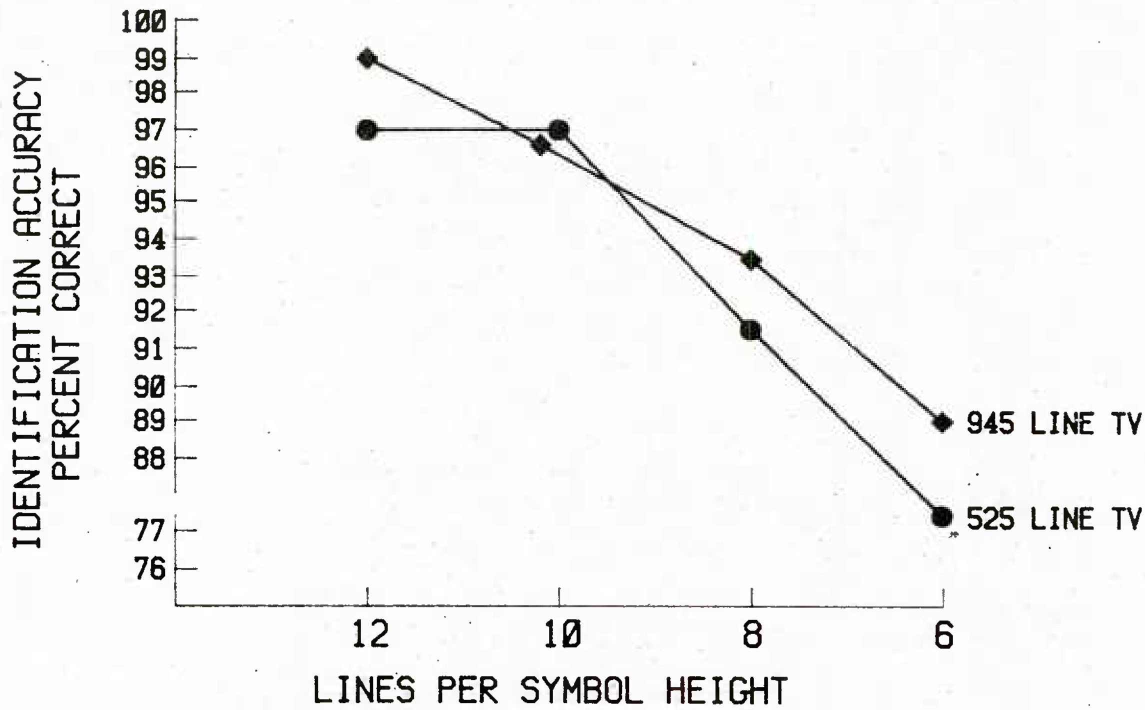


Figure 108. Accuracy of symbol identification for high and low quality TV.

4.15 Ratio of Widths of Inactive to Active Elements

Where symbol resolution is lowered (5-7 lines), the ratio of widths of inactive TV to active TV elements should be no more than 1:1. Ratios greater than this increase errors of identification as well as producing a raster that requires especially careful registration of scan lines (Shurtleff, 1966b).

4.16 Light/Dark Contrast

Light symbols (L) on a dark background are recognized more accurately under low ambient lighting. Dark symbols (D) on a light background are recognized more readily under medium and high ambient illumination (see Table 23). For intermediate values of symbol and background brightness, the direction of contrast is not significant for legibility (Blackwell, 1959). Under high ambient illumination, identification accuracy is so poor (66-73%) that the D/L condition would not be used anyway (Shurtleff, 1967).

Contrast ratio should be maintained at 90 percent.

Table 23

Accuracy in Identification in Percentage Contrast for Two Directions of Contrast and Three Values of Ambient Illumination

Direction of Contrast	Ambient Illumination		
	0.026 fc	186.4 fc	638.4 fc
D/L	88%	81%	73%
L/D	93%	77%	66%

4.17 Display Format

The effect of vertical vs. horizontal arrangement of coded symbols is negligible.

4.18 Spacing

At low brightness (1 fL), spacing of characters (25% of character dimensions) does not affect acuity. At higher brightness (20 and 40 fL), wider spacing (200% of character dimensions) produces better acuity. Wider spacing produces better acuity for L/D symbols than for D/L symbols (Shurtleff, 1967).

Banks et al. (1982) present the following recommendations for character line/column spacing:

a. EG&G--Variable from 1.7 to 35 mm depending on viewing distance. Viewing distances range from .5 to 10 m.

b. TUB--"The distance between two characters should be such that when the maximum possible character light density is set, the characters do not affect each other or do so only minimally." Minimally here means less than 5 percent, with between-character spacing of 50 percent of character width.

c. DIN--A minimum of one dot position or 10 percent of character width between characters. A minimum of one dot position or 10 percent of character height between lines, ascenders and descenders must be considered.

d. U of L--One character height between lines, one-half character width between characters.

e. VDT--100 to 150 percent of character height between lines, 20 to 50 percent of character height between characters.

f. MILSTD--One stroke width for character spacing minimum.

Buckler (1977) indicates that a large range of spacing ratios is acceptable. Symbol spacing 50 percent of letter width seems to be a middle value, while values ranging from 25 to 200 percent have been shown to be acceptable. He warns, however, that extremely large values (over 100%) should be applied with caution, especially if word information is to be presented. He recommends symbol spacing values between 26 and 63 percent for electronic display applications.

4.19 Viewing Angle

The angle subtended at the viewer's eye from the center line of the display is the viewing angle. Errors and reaction time in recognizing briefly exposed common 5 letter words increase gradually as the viewing angle is reduced from 90 degrees (straight on) to 45 degrees. At 30 degrees (60 degrees from perpendicular or straight on), the error rate cannot be accepted (see Figure 109) (Kinney, 1965).

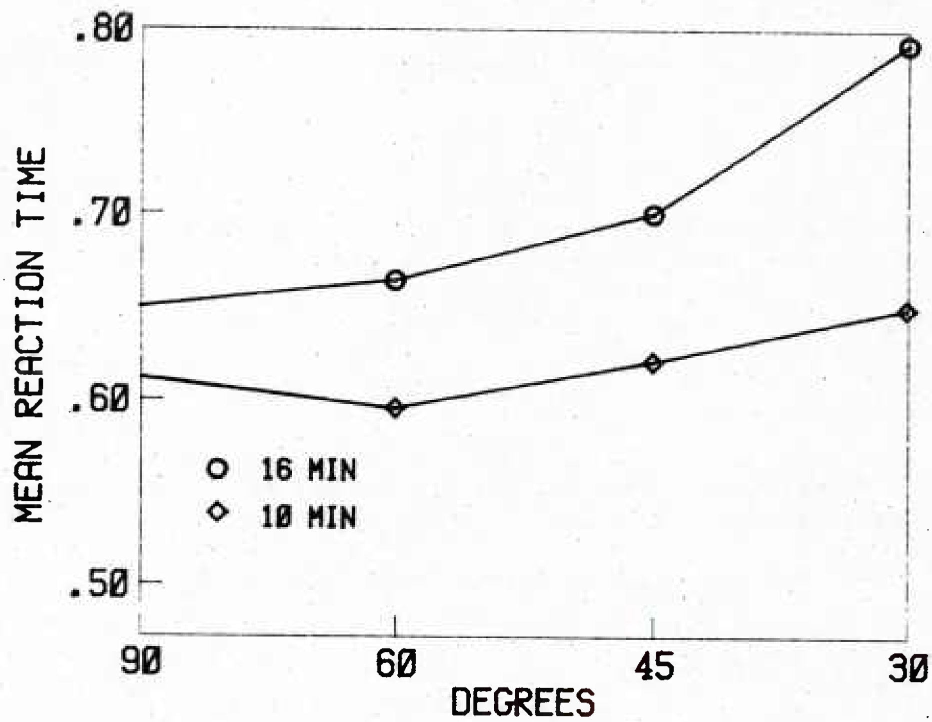


Figure 109. Mean reaction time plotted against viewing angle for two symbol sizes.

Recommendation: Optimally no viewer should be seated at a viewing angle more than 60 degrees from perpendicular or at a distance from which the height of the smallest symbol is smaller than 16 minutes of arc.

For 99 percent accurate identification, Table 24 presents the minimum required visual sizes in minutes of arc for 5 viewing angles and 2 levels of symbol resolution (high contrast symbols used).

Table 24

Visual Sizes[a] Required for Viewing TV Displays at Varying Angles

Symbol Resolution in Lines	Viewing Angle in Degrees				
	90	75	60	45	30
10	20	24	28	36	63
8	24	28	32	44	--

[a]In minutes of arc.

4.20 Exposure Duration

Minimum exposure duration for maximum visual acuity is about .2 sec with no appreciable increase in acuity beyond this minimum (Crumley et al., 1961).

4.21 Flicker

The curves in Figure 110 represent the critical flicker frequency (the lowest frequency that can be perceived as anything but a steady light) for several common phosphors as a function of display luminance (brightness).

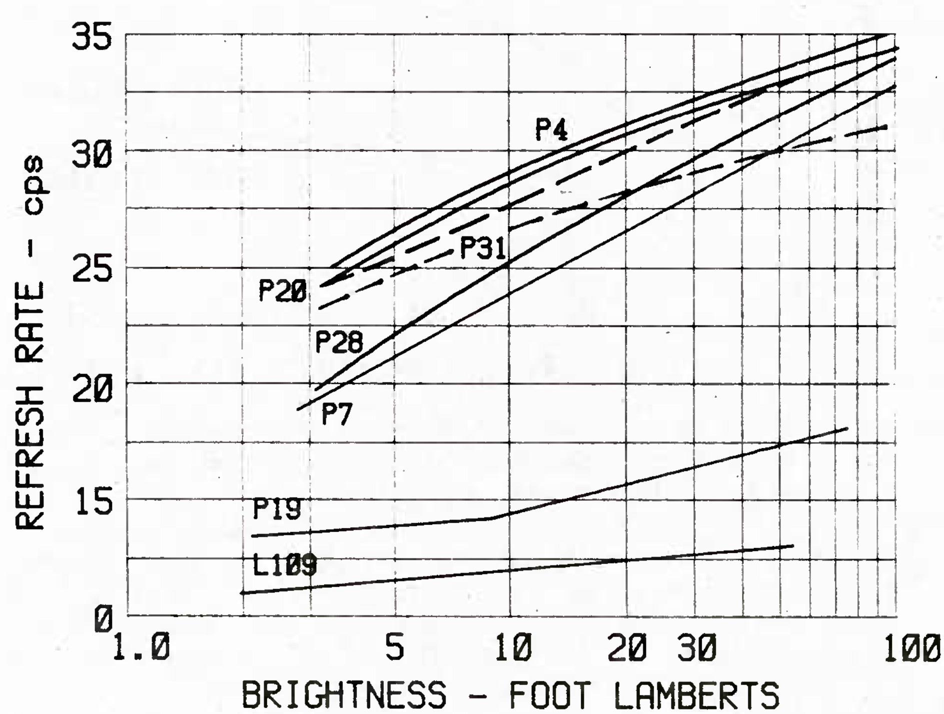


Figure 110. Flicker threshold of average observer for various phosphors (Bryden et al., 1965).

For character displays, the pulse rate should be greater than 30 to 40 Hz so that the characters do not appear to blink or flicker. Flicker can be eliminated from most electronic displays if the pulse rate is 35 Hz or more. Some flicker is noticed with average display brightness unless repetition rate is at least 50 Hz. Displays under 20 Hz are usually quite annoying to the observer (Poole, 1966).

Flicker in TV cannot be noticed at 60 fields per second unless display brightness exceeds 180 fL. If display brightness drops to 30 fL, 50 fields per second is acceptable.

4.22 The Effects of Surround Brightness on Visual Comfort

Figure 111 presents mean values of surround brightness preferred by viewers of broadcast television for three surround areas at each of five values of peak screen luminance (Shurtleff, 1966a).

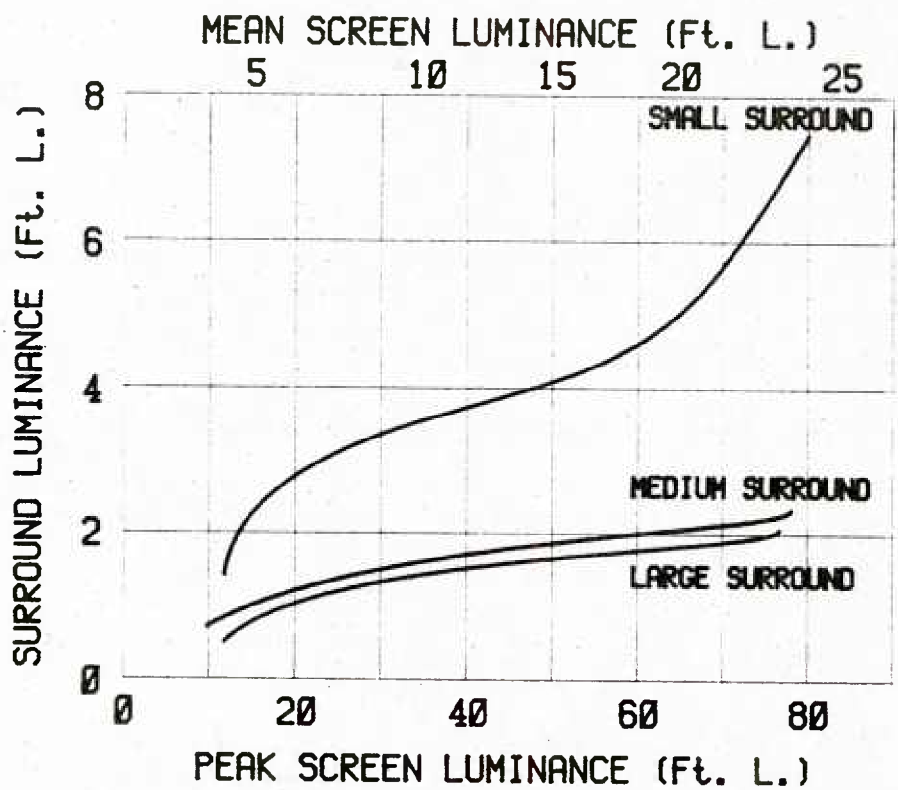


Figure 111. Mean value of surround brightness preferred by viewers of broadcast television for three surround areas at each of five values of peak screen luminance.

TV display = 9° vertically, 12° horizontally
Small surround area = 12° vertically, 14° horizontally
Medium surround area = 17° vertically, 23° horizontally
Large surround area = 23° vertically, 32° horizontally

4.23 Effects of Signal-to-Noise Ratio

One aspect of display quality affecting display acceptance and operator performance is the signal-to-noise ratio of the display. Quality of presentation has been judged satisfactory at 10:1, good at 30:1, and excellent at 50:1 (Bogatov, 1966). Table 25 provides the percentage of comments in a specific category vs. signal-to-noise ratio (Altman et al., 1968).

Table 25

Percentage of Comments in a Given Category vs. Signal-to-Noise Ratio

Comments	50dB	45dB	40dB	35dB	30dB
Impairment only slight (if at all)	98%	90%	65%	35%	10%
Not objectionable	99% to 100%	96%	85%	60%	30%
Somewhat objectionable	--	4%	10%	20%	25%
Definitely objectionable	--	--	5%	20%	45%

4.24 Effects of Blur

Figure 112 (Howell & Kraft, 1959) indicates some loss in identification accuracy for each increase in blur, where the blur (in a projection system) was defined as the ratio between the width of the transition gradient from figure to ground (on the projection screen) and the original stroke width of the letter. For the character sizes evaluated, the relative blur gradient was the same percentage of symbol stroke width, even though the absolute size of the gradient increased as the visual size of the character increased. No meaningful loss in rate of identification (symbols per second) was observed.

Shurtleff (1980) recommends that CRT beam defocussing should be kept to a minimum, although slight defocussing, which increases stroke widths up to 20 percent, can be tolerated with little decrease in identification accuracy. Blur effects can be minimized by use of large symbol sizes that subtend at the eye between 16 and 37 minutes of arc and by the use of high contrast ratios of 13:1 to 38:1.

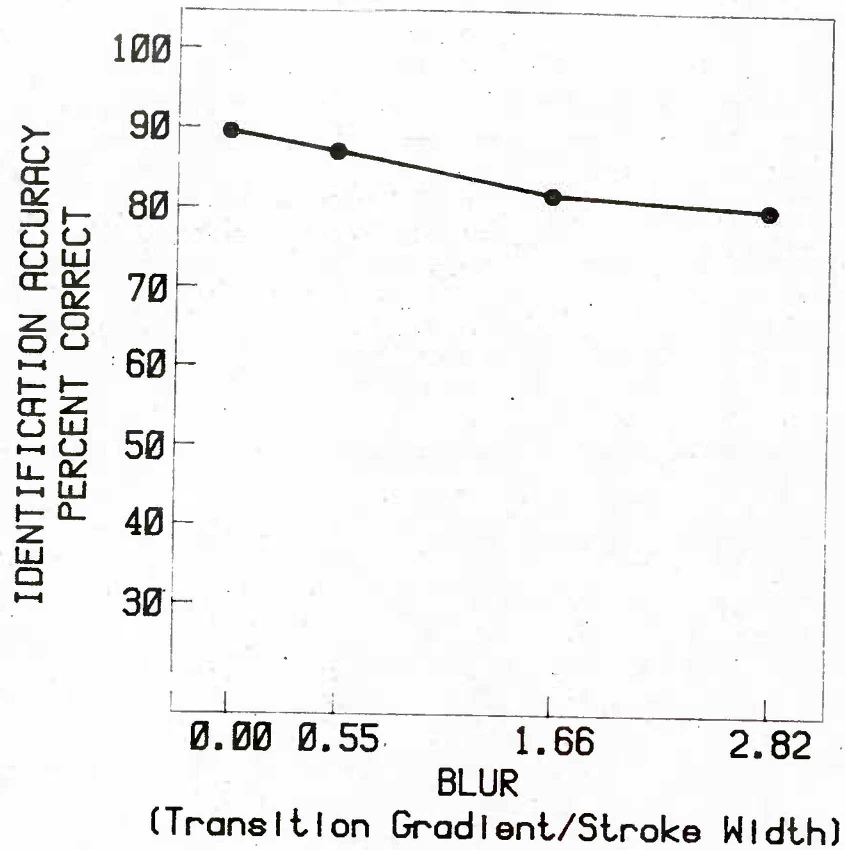


Figure 112. Relationship between symbol blur and identification accuracy.

4.25 Display Font

So far, experimental study has failed to substantiate the notion that the legibility of TV symbols will be enhanced by the development of a unique font. Any of the following is satisfactory: Leroy; Lincoln/Mitre, NAMEL, and Hazeltine.

4.26 Display Height

Recommendations with regard to display height include:

a. TUB--The top edge of the screen should be below eye height and the line of sight should intersect the center of the screen when the line of sight is lowered 20 degrees from the horizontal.

b. DIN--The upper edge of the display must be within a range from 37 to 52 cm above the work surface. It should be placed as low as possible within the range. If the display is inclined backward, the height must be reduced accordingly.

c. IBM--It depends upon the current display technology used.

d. DCIEM--Center of screen to be 10 to 20 degrees below the observer's eye position.

e. VDT--Upper edge of the screen at or below eye height.

4.27 Screen Orientation

Recommendations with regard to screen orientation vary:

a. EG&G--Screen orientation should be adjustable.

b. TUB--Vertical.

c. DIN--Vertical, if not adjustable. If adjustable, then the range should not be more than 5 degrees forward and not more than 20 degrees back from the vertical.

d. DCIEM--Surface of the screen should be within 5 degrees of a plane normal to the line of sight.

e. SNBOSH--Screen orientation should be adjustable.

Glare control was the primary consideration for the TUB recommendation for a vertical screen orientation (Cakir et al., 1978). The discussion states that there is no noticeable distortion of the image at screen inclination below 40 degrees relative to the line-of-sight. For that reason, TUB states that the screen may be placed in a vertical plane without any loss in character quality and eliminate much of the screen reflection problem. DIN makes the same recommendation for a fixed-screen orientation and provides a maximum range of adjustability for tiltable displays. It is not clear why such a recommendation was made. The DCIEM recommendation that the screen surface should be within 5 degrees to a plane normal to the line of sight appears to be overly restrictive (Gorrel, 1978). Glare control is the reason for the SNBOSH requirement that the display screen should be adjustable (Swedish National Board of Occupational Safety and Health, 1979). It is not known if that requirement would be relaxed if the glare problem were solved in a different way.

From a human factors viewpoint, these recommendations seem overly restrictive. Perhaps, it would be better to allow the user to adjust this particular variable personally rather than to prescribe some fixed point or angle.

4.28 Group Displays

This section discusses the parameters most important for group viewing of TV displays.

a. Symbol size. In a group viewing situation, letters must be large enough to produce at least 8 minutes of visual angle (preferably 14 minutes) at the eye of the observer in the worst position in the viewing area (30 degrees off-axis). This should produce 95 percent accuracy of identification of random characters (Neal, 1968).

b. Viewing angle. Under conditions where resolution (lines per character) and symbol size produce at least 90 percent identification accuracy at 0 degrees off-axis (90 degrees straight on), there is no decrement in legibility until the off-axis angle becomes 40 degrees. Under less favorable size and resolution conditions, the effect of the off-axis angle is more severe, reducing legibility significantly at 20 degrees (see Figure 113) (Neal, 1968). The maximum off-axis angle should be 30 degrees.

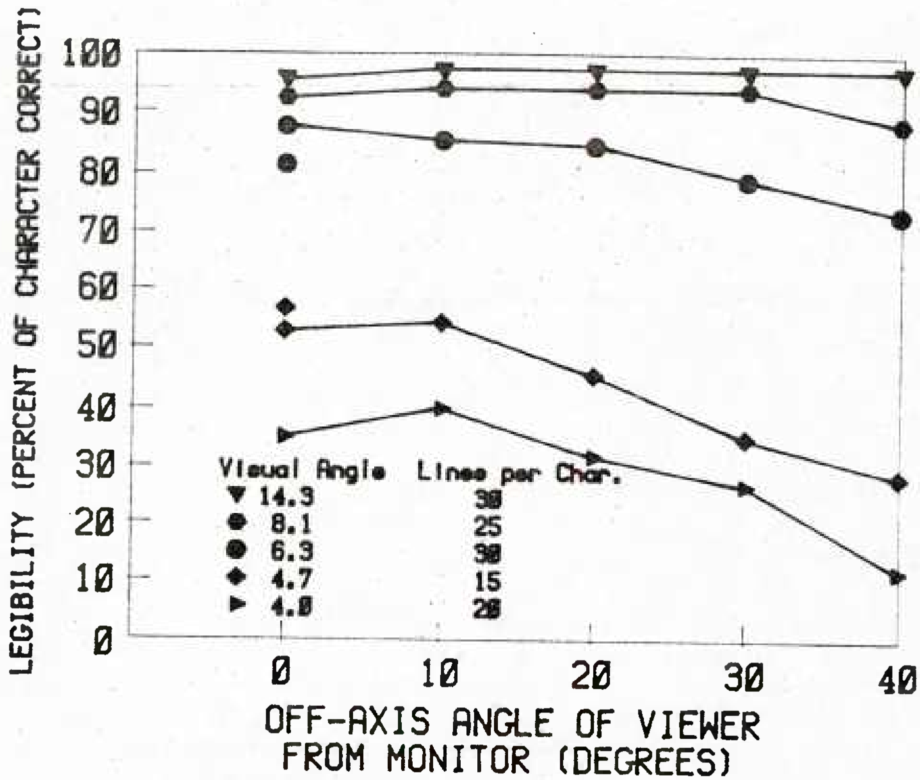


Figure 113. Average legibility as a function of off-axis angle for five representative test conditions.

The adverse effect of oblique viewing is not a straight conic projection from the screen, but rather is geometrically described by "the surface of a sphere tangent to the plane of the display." The diameter of that sphere equals the recommended viewing distance for that particular display size. Figure 114 presents the locus of marginal legibility for a constant visual angle (Luxenberg & Kuehn, 1968).

c. Resolution. For group viewing, a minimum vertical resolution of 15 lines per character height is recommended when small visual angles are involved. At 15 lines per character, the ratio of the character height to the total display height is 1/33 and 16 rows of characters can be put on the screen (as long as the screen is close enough to keep the visual angle within 8 minutes of arc) (see Figure 115) (Neal, 1968).

d. Bandwidth. For group viewing of a large television screen (17 inches or more), a bandwidth of approximately 2.5 MHz is recommended. There is no improvement above this point, but decrement below it.

e. Choosing the maximum viewing distance from the screen. Figure 115 shows the maximum viewing distance from various size monitors calculated to maintain the recommended minimum visual angle (8 minutes). For a symbol resolution of 15 lines, the recommended maximum distances for various monitor sizes are:

(1) 27-inch monitor--18 feet.
(2) 24-inch monitor--15 feet.
(3) 21-inch monitor--13 feet.
(4) 17-inch monitor--11 feet.

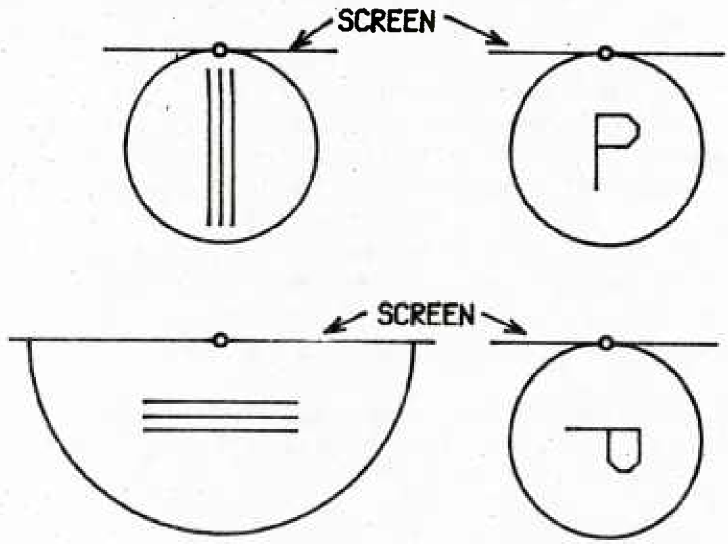


Figure 114. Loci of marginal legibility for resolution bars and letter P. The symbols are displayed at eye level on a vertical screen, above in upright position, below turned horizontal. The locations of the symbols are indicated by the small circles.

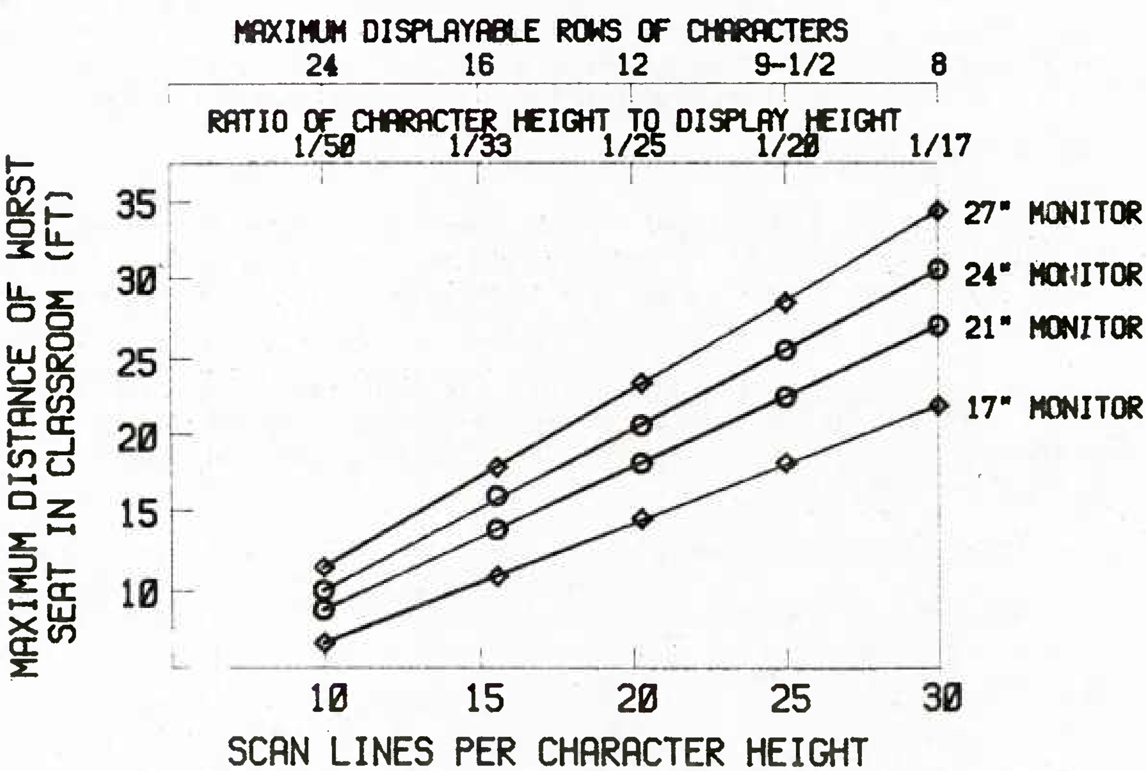


Figure 115. Maximum viewing distance (in feet) for worst seat in classroom maintaining a minimal 8 minutes visual angle at the eye (Neal, 1968).

Another way to increase the maximum viewing distance is to choose larger characters, although this will reduce the total number of characters that can be placed on the display. For example, Figure 115 shows that, as the character height increases from 1/33 of screen height (15 scan lines) to 1/17 (30 lines), the maximum viewing distance increases from 18 to 35 feet from a 27-inch monitor or from 11 to 22 feet from a 17-inch monitor. However, the maximum number of rows of characters that can be placed on the screen decreases from 16 rows with the smaller characters to 8 rows with the larger.

f. Response time. Response time is the major, if not the only, justification for automating display systems. The faster a requested display becomes available upon request, the greater is the impact that the display has on system operations. Request response time should be on the order of 1 to 2 seconds.

Display generation response time is defined as the time from initiation of computer output until the complete display is available to the user; 1 to 2 seconds is desirable.

g. Brightness.

(1) Brightness ratios required for comfortable viewing of large screen displays may be determined by locating (a) the minimum ratio required for adequate viewing and (b) the maximum measure of brightness without annoying aftereffects. The maximum brightness of group displays should not be more than 35 fL. Higher brightness may produce afterimages if the display is viewed for an extended period of time. An increase in brightness over 15 fL up to the 35 fL maximum contributes little to acuity.

(2) An optimum brightness distribution on the surface of the display is approximately 17 fL measured from central axis; and not less than 13 fL measured at the largest angle of view off center. Assuming an ambient light level of 1 fc on the display, this permits viewing in about 10:1 contrast for symbols with regard to background.

(3) Brightness contrast should be maintained at 90 percent.

h. Ambient illumination. To minimize glare, light sources should not be located within 60 degrees of the viewer's central visual field. Light should be diffused and distributed evenly over the work area. The ratio between light and dark portions of work surfaces should not exceed 7:1.

i. Registration accuracy. The maximum symbol registration accuracy considered necessary is 10 seconds of arc with respect to the nearest observer. Registration requirements more accurate than this are unnecessary, since an observer cannot appreciate the difference.

4.29 Optical Projection Devices

This section discusses the display characteristics of projected images (i.e., slides, films, remotely projected CRT displays, etc.). Table 26 presents recommended values for some of the factors.

a. Symbol size. The acceptable visual size for viewing projected alphanumeric characters is between 10 and 15 minutes of arc resolved at the viewer's eye. This follows from essentially the same performance results of research on TV displays.

Table 26

Other Factors in Group Viewing of Optical Projection Displays

Factor	Optimum	Preferred Limits	Acceptable Limits
Ratio of $\frac{\text{viewing distance}}{\text{screen diagonal}}$	4	3-6	2-8
Angle off centerline	0°	20°	30°
Image luminance (no film in operating projector)[a]	10 fL (34 cd/m^2)	8-14 fL (27-48 cd/m^2)	5-20 fL (17-69 cd/m^2)
Luminance variation across screen (ratio of maximum to minimum luminance)	1	1.5	3.0
Luminance variation as a function of viewing location (ratio of maximum to minimum luminance)	1	2.0	4.0
Ratio of $\frac{\text{ambient light}}{\text{brightest part of image}}$	0	0.002-0.01	0.1 max[b]

[a]For still projections, higher values may be used.

[b]For presentations not involving grey scale or color (e.g., line drawings, tables .2 may be used.

b. Aspect ratio. Aspect ratios between 1.33 and 1.48 (height per width) are recommended for greatest legibility. Stroke width should be in the range of 1/6 to 1/10 character height. Figure 116 presents screen dimensions as a function of aspect ratio.

c. Viewing distance. Viewing distance for projected displays are determined by a number of factors including resolution of picture detail, limitations of graininess, and sharpness in the projected image, etc. Recommended viewing distances for small viewing areas (CICs, etc.) and auditoriums, etc. are listed in Table 27.

d. Viewing angle. The maximum recommended viewing angle for group viewing of slides and motion pictures is between 20 and 30 degrees off the center line of the display. Objectionable geometric distortions of the image on a flat screen become apparent at angles beyond approximately 30 degrees off-axis to the screen.

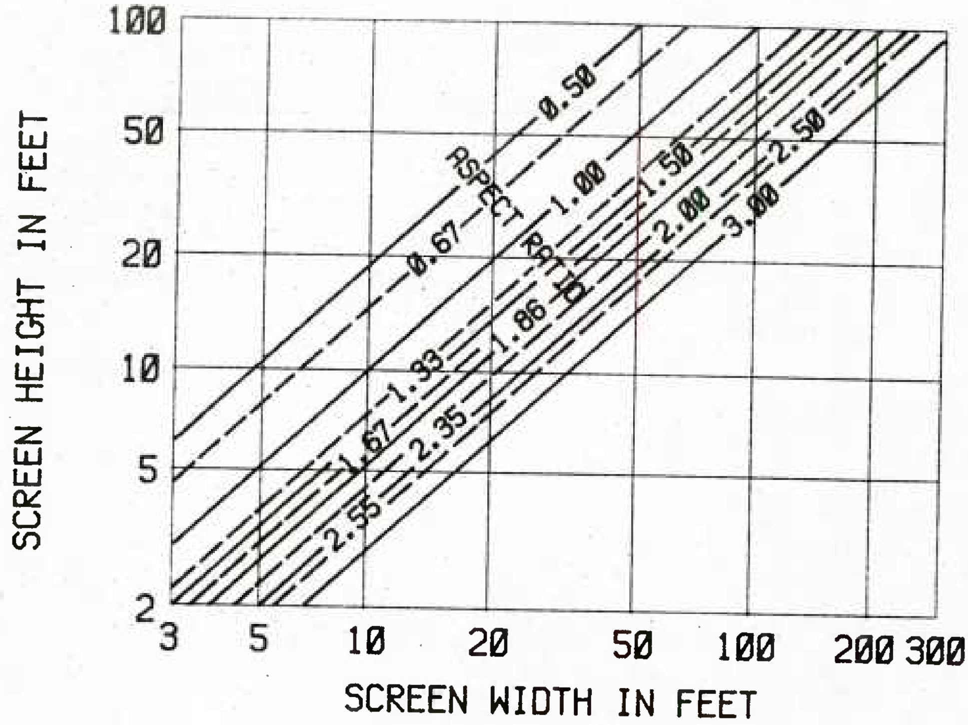


Figure 116. Screen dimensions as a function of aspect ratio (Illumination Engineering Society, 1959).

Table 27

Recommended Viewing Distances

	Small Rooms	Auditoriums
From Row of Seats	3.0	1.2
Minimum Viewing Distance	3.0	1.2
Maximum Viewing Distance	5.0	8.0

Note. Dimensions given are in multiples of screen height.

e. Image luminance. Screen luminance levels (measured with no film in the projector) are approximately 10 times the average luminance level of the images projected from normal films. Illumination falls off from the center as a function of screen type, decreasing as much as 20 to 40 percent at the screen's edge. The recommended screen luminance for small rooms, auditoriums, and theatres being 10 fL (Illumination Engineering Society, 1959).

Luminance variation across the screen should be held to 1:5 for:

$$\frac{\text{Maximum Illumination}}{\text{Minimum Illumination}}$$

f. Direction of light/dark contrast. Direction of contrast has not been proven to have any appreciable effect on detection performance.

g. Contrast ratio. The recommended contrast ratio for viewing optically projected displays is 500:1, measured with no film in the projector (maximum image highlight brightness will normally be 25 to 60 percent of screen brightness).

h. Projection screen types. One of the primary factors responsible for the performance of optically projected systems is the type of projection screen used. Screens can be classified generally as reflective or translucent, depending upon whether the projected image is viewed from the same side as the projector (reflective) or from the opposite side (translucent). Reflective types may be either directional or nondirectional depending on whether or not brightness changes with viewing angle.

(1) Mat screens. Mat screens are practically nondirectional. Screen brightness is essentially the same at all viewing angles. Practical reflective mat screens have surfaces of high reflectance but, since the light is distributed throughout a complete hemisphere, the maximum attainable brightness is limited. Most mat screens are about 85 to 90 percent efficient.

(2) Lenticular and metallized screens. Reflective or translucent screens incorporating uniformly shaped and spaced lens-elements and/or metallized surfaces control the direction of light reflection so that maximum brightness will be obtained within certain specified viewing angles. The highest brightness for a given incident illumination is obtained with screens having lenticulated surfaces. Gain is typically 1.5 to 2.0 relative to a nondirectional screen.

(3) Beaded surface. A beaded surface may be either a reflective or translucent screen. Such a screen will appear to be brightest when viewed along the axis of projection and will darken quite rapidly as the viewing angle increases away from the axis. Gain is typically 1.5 to 3.0.

Figure 117 presents the efficiency of various types of screens as a function of viewing angle.

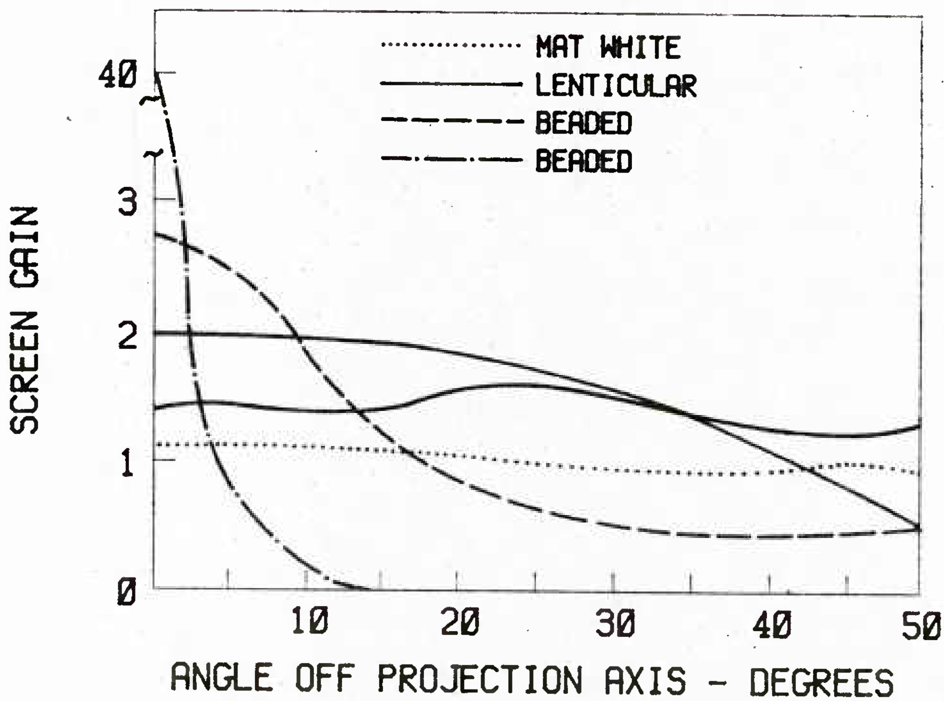


Figure 117. Gain vs. viewing angle for typical front projection screens (Baker & Grether, 1954).

SECTION 5

SELECTION OF NEW DISPLAY TECHNOLOGIES

5.0 SELECTION OF NEW DISPLAY TECHNOLOGIES

5.1 Introduction

Snyder (1980) suggests a generalized design procedure that permits the human factors/system engineer to proceed from display requirements to selecting or evaluating a specific display technology or device. Figure 118 illustrates that procedure, which consists of the following individual steps.

a. Define display functional requirements. Having, as a function of mission analysis, function allocation and display control information requirements analysis, determined the types of symbols, pictures, etc., to be displayed on the electronic device, it is then necessary to answer the following questions:

(1) What is the display/observer geometry?

(2) What environmental/power constraints exist?

(3) What is the nature of the ambient illuminance?

(4) What symbology must be displayed?

(5) Is dynamic presentation required? If so, at what data rates?

(6) Is the displayed information alphanumeric, vector-graphic, pictorial, or some combination of these?

(7) How much of this information must be presented simultaneously, and in what format?

Answers to these questions define the functional requirements of the display, which are then used to generate more specific design or performance requirements.

b. Define display design requirements. The functional display requirements indicate what information is to be displayed, where, when, and how often. The design requirements, on the other hand, specify the exact design variables to which the hardware (and software) must conform to ensure adequate operator performance.

The functional requirements are compared with our knowledge of operator/display relationships to generate more detailed design requirements for the display hardware.

Snyder and Maddox (1978) feel that, as a minimum, the following variables must be specified in the design requirements:

(1) Display size.
(2) Resolution.
(3) Element density.
(4) Element size, shape, spacing.
(5) Element uniformity.
(6) Geometric linearity.
(7) Noise or signal/noise ratio.

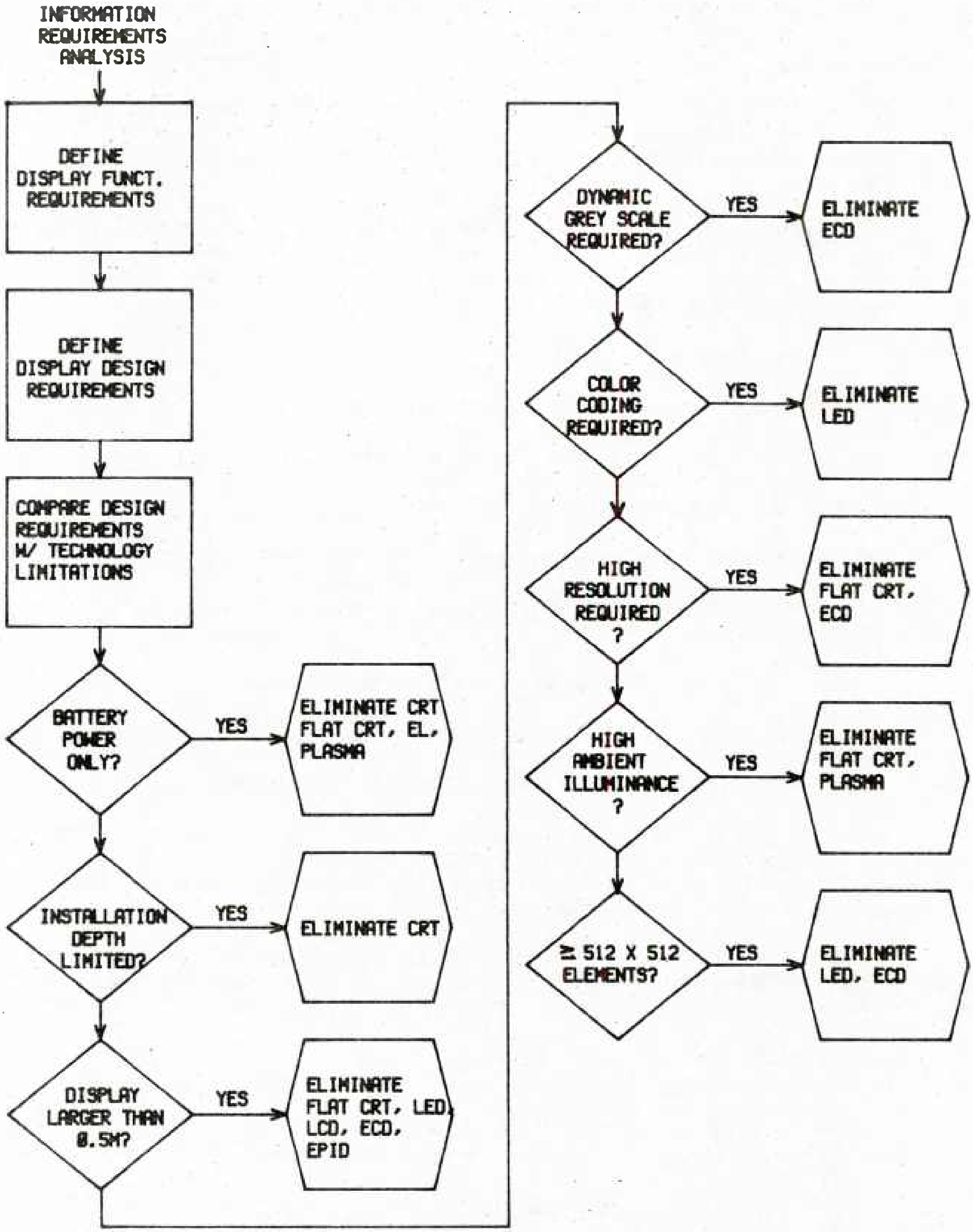


Figure 118. Flow chart for display technology selection (taken from Snyder, 1980).

(8) Rise, fall times.
(9) Persistence.
(10) Refresh rate.
(11) Color.
(12) Luminance and dynamic range.
(13) Viewing angle.
(14) Symbol, character fonts, sizes.
(15) Graphics format.
(16) Power, voltage limitations.
(17) Installation constraints.

Some of these were encountered in Section 1.0.

c. Compare design requirements with technology limitations. The display design requirements, once specified, can be compared directly with the capabilities and limitations of the alternate technologies to eliminate those technologies incapable of meeting specific design requirements. If this process is applied in an overly rigid manner, it will result in the elimination of all candidate technologies, since requirements are often derived under worst-case conditions and there is no all-purpose, ideal display technology. Thus, tradeoffs are inevitable.

Nonetheless, Figure 118 and the following steps will result in logical elimination of totally unacceptable technologies and will permit the identification of variables suitable for tradeoff. At each of the following steps, design variables are used to eliminate candidate technologies/devices based upon design requirements (see Table 28).

The following parameters should be considered:

(1) Power voltage--The CRT requires 10 to 15 kilovolts and about 100 watts to operate and, therefore, cannot be driven by batteries for sustained periods. Similarly, the flat CRT, EL, and plasma displays require over 100 milliwatts per cm^2 of power and are not battery compatible.

(2) Installation depth--The prime reason for finding an alternative to the conventional CRT is to reduce the depth behind the display. If only a few centimeters of depth are available, the CRT must be eliminated.

(3) Large display size--Multioperator requirements for displays larger than .5 m eliminate from consideration the flat CRT, LED, LCD, ECD, and EPID. However, projection systems using an LCD light valve may be in competition for some limited ambient illuminance situations.

(4) Dynamic grey scale--Dynamic shades-of-grey video requirements (e.g., television) will eliminate from consideration the ECD.

(5) Color coding--Flexible and variable color coding eliminates the LED and is compatible with the EL, plasma, LCD, ECD, and EPID under limited circumstances only. Typically, flexible, dynamic color coding will require selection of the CRT or flat CRT.

(6) High resolution--While various applications demand different resolution limits, if one assumes "high resolution" to imply element densities of at least 3.25 per mm, then the flat CRT and ECD are usually eliminated from consideration.

Table 28

Qualitative Comparison of Technologies by Design Variables (taken from Snyder, 1980)

Technology	Size	Power/ Voltage	Color Capability	Luminance Capability	Resolution	Dynamic Range	Uniformity	Matrix Addressing	Cost
Cathode-ray Tube (CRT)	Miniature to large projection	high	yes	low to high	high	yes	fair	yes	low
Flat CRT	small	medium	yes	low to medium	medium	yes	fair to good	yes	high
Light-emitting Diode (LED)	small	low	limited	low to very high	high	yes	good	no	low
Electroluminescent (EL)	small to large	medium to high	limited	low to high	high	yes	fair	yes	high
Plasma	small to medium	high	possible	medium	medium	yes	good	yes	high
Liquid Crystal (LCD)	small to medium	low	limited	n/a	medium	yes	good	yes	low to medium
Electrochromic (ECD)	small to medium	low	discrete	n/a	unknown	no	good	no	low
Electrophoretic (EPID)	small to medium	low to high	discrete	n/a	medium	yes	good	probably	low

(7) High ambient illuminance--Although contrast-enhancing filters can be very useful, some technologies cannot meet minimum contrast requirements under high (e.g., 5000 lux) ambient illuminance. Those eliminated for this reason will typically include the flat CRT and plasma displays, and often the CRT and EL.

(8) Large element arrays--Displays requiring at least 512 x 512 element arrays eliminate from consideration the LED and ECD.

Other considerations, such as cost or compatiblity with raster addressing, may also serve to eliminate certain technologies or display units. As in all systems design activities, however, the selection or elimination of specific items should be made on the basis of quantitative tradeoffs and analyses. The items described above constitute only a "shopping list" and general approach.

5.2 Technology of Flat Panel Displays

5.2.1 Introduction

This section, which is taken almost wholly from Synder (1980), discusses the technological aspects of displays other than the conventional CRT: flat panel CRT, light emitting diode (LED), electroluminescence (EL), plasma, liquid crystal, electrochromic, and electrophoretic displays. This information is current as of 1980 and new developments in a fast moving field may have rendered certain judgments obsolete.

To provide a basis for comparison of the pertinent technologies, each of the display technologies is described relative to a set of 13 categories or parameters. These categories range from physical/engineering characteristics (size, configuration, power requirements, addressing requirements) through visual system pertinent variables (spectral emission, luminance, element size, element shape, contrast, uniformity, temporal characteristics) to cost and include more subjective comments about the utility of the technology for three categories of information presentation.

Finally, a future technology projection is offered for each category. Each of the 13 categories is defined below.

a. Physical size and configuration. This category describes the typical size and the range of physical sizes over which the display type can or may be fabricated. In some cases, the discussion refers to commercially available sizes, in other cases to potentially available sizes. In a couple of cases, limits to size are noted, as constrained by the inherent technology characteristics.

b. Power and voltage requirements. Although power and voltage requirements for a given device or application are typically of greater concern to the device designer, the user must also be aware of these requirements. A specific application may have some types of power available (e.g., direct current) but not others. Similarly, some applications have severe power limitations (e.g., personally carried, portable display). Thus, total power and voltage requirements remain the concern of the human factors engineer as well as the device designer.

c. Spectral emission. The human visual system is not equally sensitive to all wavelengths of visible light energy. Accordingly, wherever possible, the spectral emission is given in either radiant or luminous energy per unit bandwidth. Bandwidth is expressed in nanometers (1 nm = 10^{-9} m).

d. Luminance. Because the visual system is not equally sensitive to all wavelengths of visible radiant energy, the radiant energy (in watts per nm) must be weighted by the sensitivity of the eye to that wavelength, a function termed the photopic luminosity function. The eye is most sensitive in the middle, or yellow-green, section of the visible spectrum and least sensitive at the extreme red (long-wave) and blue (short-wave) ends.

The weighting of radiant energy by the photopic luminosity function produces the physical measure of luminance, candelas/square meter (cd per m^2). Units often used, include the foot-Lambert (fL) and milliLambert (mL) (1 fL = 3.426 cd per m^2).

e. Luminous efficiency. Not all devices produce the same amount of emitted radiant energy per unit of electrical power consumed. To permit comparison of devices, in terms of their efficiency in converting electrical into radiant energy, the concept of radiant efficiency, measured in radiant watts/electrical watts, is used. However, because all radiant energy is not equally visible to the observer, it is more meaningful to weigh the emitted radiance by the photopic (daytime) luminosity function to provide the ratio of luminous energy to electrical power (luminous efficiency), expressed in lumens per watt (lm per W).

f. Element size, shape, density. Flat panel displays are generally segmented in one of two forms. Some alphanumeric readouts are designed as seven-segment or starburst patterns (Figure 119) in which selective addressing creates any specified alphanumeric. The other form is an element matrix in which the elements are arranged in an X-Y array. By selective addressing of various elements in the X-Y array, one can create alphanumerics, symbols, line graphics, solid (shaded) areas, or even pictorial information such as a commercial TV image.

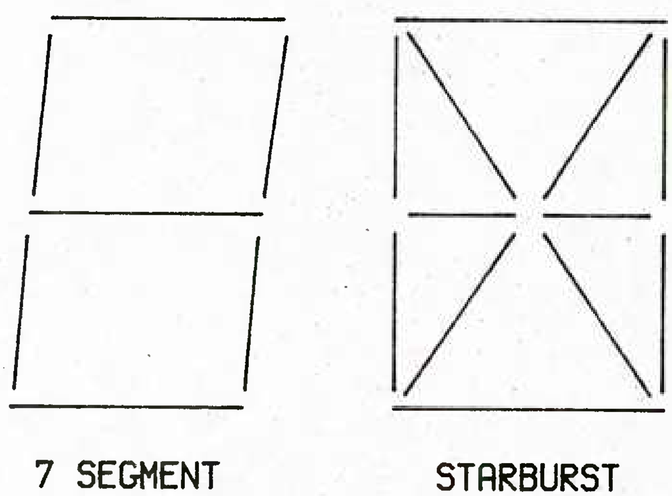


Figure 119. Seven-segment and starburst alphanumeric patterns.

In recent years there has been rapid growth of the number of flat panel matrix designs. Readibility and legibility of X-Y matrix addressed displays are significantly affected by individual element size, element shape, and spacing between elements (Snyder & Maddox, 1978). Element size can be specified in terms of diameter, length and width, and angular subtense units. Element shape can be specified in terms such as round, square, rectangular, Gaussian, etc. Spacing between elements is edge-to-edge, or centerline. If element edges are poorly defined, center-to-center specification is more valid.

g. Contrast and dynamic range. Another important parameter is the contrast between any "on" display element and its "off" background. If the maximum or "on" luminance is symbolized as L_{max} and the background or "off" luminance is indicated by L_{min}, then the following definitions hold:

$$\text{Modulation (M)} = (L_{max} - L_{min}) / (L_{max} + L_{min}) \quad (5.1)$$

$$\text{Contrast ratio (CR)} = (L_{max} / L_{min}) = (M + 1) / (1 - M) \quad (5.2)$$

$$\text{Dynamic range} = (L_{max} - L_{min}) = L_{max}(2M) / (M + 1) \text{ or} \quad (5.3)$$
$$= L_{min}(2M)/(1 - M)$$

$$\text{Relative contrast (C)} = (L_{max} - L_{min})/L_{min} = (2M) / (1 - M) \quad (5.4)$$

Shades of grey refers to the number of just distinguishable increments in luminance that can be detected on a display. "Good" displays are said to produce 10 to 12 shades of grey.

A shade of grey increment is arbitrarily defined as equal to a $(2)^{.5}$ luminance increment. This can be misleading if one thinks of shades of grey as perceptual units. Because the concept of modulation M is quite useful in display design and because $(2)^{.5}$ shades of grey (1.414 size steps) are often reported, the following equation is noted:

$$(2)^{.5} \text{ shades of grey, } N = 1 + \left[\frac{\log \frac{(1 + M)}{(1 - M)}}{\log (2)^{.5}} \right], \quad (5.5)$$

for L_{min} greater than zero. This equation applies only to the special case of one shade of grey. A more general equation is:

$$N = \log(L_{min})/\log 2^{.5}) + \frac{\log (1+M)/(1-M).}{\log 2^{.5}} \quad (5.6)$$

h. Uniformity. Display uniformity is best defined by nonuniformity. Three types of nonuniformity can be distinguished:

(1) Large area nonuniformity is a gradual change in luminance (or color) from one area of the display to another, such as center-to-edge or edge-to-edge comparisons and gradients.

(2) Small area nonuniformity pertains to element-to-element changes in luminance (or color) over small areas.

(3) Edge discontinuity refers to changes in luminance or color over an extended boundary.

In this section, subjective estimates of uniformity, physical measures (e.g., element failure rates), and applied specifications will be stated where they exist.

i. Temporal characteristics. Some flat-panel displays have inherent memory--an element turned "on" will remain on until it is turned "off." Most technologies, however, have persistence display elements that require periodic "refreshing" to avoid a perceived reduction in luminance over time or perceived flicker. To determine the required refresh rate to avoid perceived flicker, one must know the rise time and fall time of the luminance of the device.

Rise time is the time required by the device to reach maximum luminance after the application of a square wave "on" pulse or command. It is usually measured in microseconds (10^{-6} second) or milliseconds (10^{-3} second).

Fall time is the time, following cessation of the "on" pulse or command, for the luminance to reach 10 percent of its maximum value. It is also measured in micro- or milliseconds.

j. Addressing/driving interfaces. A major consideration in any display system design is the electronic circuitry required to turn "on" and "off" any element or location on the display at the correct time and with the proper luminance. Some technologies are more compatible with inexpensive, reliable addressing/driving concepts than are others. "Addressing" refers to the electronics that determine which element is turned on, whereas "driving" refers to provision of the right amount of power to the element to turn it on.

Segmented or starburst alphanumeric readouts typically present no serious problems in addressing or driving. Compatible power supplies exist, the number of segments to be addressed is relatively small, the logic of selection of the "on" segments is typically simple, and the total display refresh rate is not difficult to establish or meet.

Far greater problems exist with graphic displays, matrix-addressed character displays, and video displays. For such applications, the number of elements is usually large ($512 \times 512 = 2.6 \times 10^5$ is fairly typical), and addressing each element with a pair of leads is expensive, difficult, and often physically unattainable, at least in the size domain required for effective visual displays, where there may be as many as 16 to 20 elements per square millimeter. Thus, the compatibility of any flat panel display technology with addressing/driving circuitry is critical to its potential utility.

As a basis for comparison, the conventional raster scanning of the home television addresses over 3×10^6 picture elements per second and high resolution television displays are available with the capability to address over 50×10^6 picture elements per second. No matrix addressing technique has achieved a comparable rate.

Several of the flat panel displays to be discussed later can be matrix addressed with success and acceptable results. The techniques work, but the cost can be high. The resulting complexity may be too costly to compete with the cathode ray tube.

k. Cost. The cost of flat panel displays is probably the most critical factor. Most technological problems have been or can be solved; however, the production costs far exceed the cathode ray tube for most graphics and video applications.

l. Utility for display-type applications. For convenience and directness of evaluation, four generic types of display usage or application are considered.

From a technology standpoint, alphanumeric readout of data and messages requires the least demanding type of display. Information presented on this type of display is usually constrained by an alphabet of letters, numerals, and symbols and a discrete set of locations in which any alphabet character can be located. Incandescent, mechanical, and vacuum-fluorescent devices are currently used most often for this type of display. The characters displayed can be composed of segmented, stroke, raster scanned, or dot matrix elements.

Graphics (or vectorgraphics) requirements describe a more complex type of display. Graphics displays require the ability to position curved and straight lines essentially anywhere on the display, to move those lines individually and independently often at rapid rates, to shade various display areas, and to overlay alphanumeric information on the graphics information.

A most demanding requirement of a display is to present video information, as in a television or radar display. This category typically demands the greatest resolution, rate of motion, levels of distinguishable intensities, and (potentially) color with no noticeable flicker or blur.

The last requirement is for use in a large-screen, or group viewing, situation. A "large screen" display is that required for more than three simultaneous viewers, normally a display in excess of .5 m on a side. Some large screen displays are viewed directly, while others are viewed by projection.

m. Future technology projections. For each technology and, where available, information is given on the future directions of reasearch and development.

5.2.2 Standard Cathode-Ray Tube (CRT)

For a great majority of data and imaging applications, the CRT dominates the market. Part of its popularity is due to cost, and part is due to a long lasting familiarity. The CRT is often chosen for numerous applications because of its tremendous flexibility. CRTs are available in a variety of sizes and shapes, provide grey scale and color, can have reasonably good resolution, can provide a storage capability, and can be addressed with both raster and stroke patterns.

Information on CRT display capabilities is readily available from many sources and will not be summarized here for that reason. However, for comparison purposes, the CRT are listed in Tables 29 through 41.

5.2.3 Flat-panel CRT

The conventional CRT also has a few substantial disadvantages. In many applications, a major disadvantage is its depth; as the display image size is increased, so is the length of the tube. Considerable effort has therefore been exerted to develop a CRT with much less depth (i.e., flat panel CRT).

a. Physical size and configuration. The flat panel CRT concept is best illustrated by the Northrop Corporation's DIGISPLAY (Goede, 1973). The electron area source is a cathode that is less than 12 mm thick and consists of a number of cathode elements requiring fairly low power. The modulation plate controls the electron beam current from the cathode, much as the control grid does in a conventional CRT.

The modulation plate is followed by a series of switching plates, each of which has an array of channels ("holes") which pass electrons. These switching plates accomplish two functions: (1) They keep the electron flow in well defined channels or directions, and (2) they either pass or stop the flow of electrons in a given area, by voltage addressing of each plate.

Dielectric spacers between the switching plates provide structural strength. Lastly, the electron streams impact on a monochrome or multicolor phosphor to provide a modulated image much the same as in a conventional CRT.

Due to the parallel plate design of this device, there is no particularly critical size limitation. To date, functioning DIGISPLAY devices have ranged in size from 7.37- by 11.68-cm to 16.26 cm square. Larger panels could be fabricated if the need arose. Thickness will generally be less than 5 cm.

Sherr (1979) states that the cathode power is about 100 milliwatts per cm^2, and the total power therefore ranges from 2 to 30 watts. Goede (1973) described four different DIGISPLAY devices in which the beam power ranged from .65 to 8.7 watts per cm^2 and total tube power from 1.6 to 27 watts.

b. Spectral emission. The phosphor screen may be chosen to be any of the standard phosphors. Thus, a variety of spectral emissions is possible for monochrome displays.

Multicolor displays are obtainable with two techniques: (1) the beam penetration phosphor coating, and (2) a tricolor dot phosphor screen (Goede, 1973). The spectral range of the penetration phosphor approach has the same limitations as those of the conventional CRT (i.e., color saturation will be limited by partial inadvertent activation of the nonaddressed phosphor).

In the color triad approach, the color dots are deposited in red, green, and blue triads, and each color is addressed through a separate hole or channel in the final switching plate. This approach, while theoretically feasible, has yet to be adequately demonstrated.

c. Luminance. The display luminance decreases as the number of elements scanned per unit time increases because the dwell time per element increases, much as is the case with a conventional CRT. To combat this loss of luminance, one uses multiple-beam scanning. The four devices described by Goede (1973) have from 13 to 40 beams and result in spot luminances ranging from 103 to 822 cd per m^2. Goede (1978) estimated the flat-panel CRT luminance at 103 cd per m^2.

d. Luminous efficiency. The only estimate of luminous efficiency for flat-panel CRTs is 2.0 lm per watt, offered for a 512 x 512 element TV display by Goede (1978). This is, of course, much less than that of a conventional CRT with a P4 phosphor, which typically emits about 44 lm per watt, or a P22 (color) TV CRT emitting about 8 lm per watt for a white image.

e. Element size, shape, density. Monochrome, flat-panel CRTs are limited in element density to the accuracy with which channels in the switching plates can be aligned. To date, the highest density flat-panel CRT has 3.15 elements per mm (Goede, 1973).

f. Contrast and dynamic range. Goede (1973) claims contrast ratios for four different DIGISPLAY models to range from 25:1 to 100:1 minimum. Presumably, these are the ratios of element-on to element-off luminances under zero ambient illuminance.

Goede (1973) has demonstrated a DIGISPLAY with seven $(2)^{.5}$ shades of grey, and claims that sixteen $(2)^{.5}$ shades are possible, which would require a dynamic range of 256:1.

g. Uniformity. No data are available on any form of flat-panel CRT uniformity. However, since the flat-panel CRT has many of the uniformity features that exist for solid-state panels of other types, image and geometric stability should be very good and luminous uniformity should be excellent.

h. Temporal characteristics. Since the rise and fall times of the luminance of addressed elements will result directly from the phosphor characteristics, the temporal characteristics of the flat-panel CRT should be similar to those of the conventional CRT; that is, much depends on the phosphor selection.

i. Addressing/driving interfaces. The driving voltages of the flat-panel CRT are in the tens of volts and present no particular problems. The addressing requirements vary with the plate/lead scheme. The simplest scheme is to use two leads per plate, which requires only binary addressing logic. However, as the number of elements becomes larger, so does the number of plates. Thus, a tradeoff is made between plate number and addressing complexity. For a 512 x 512 element graphic TV display, Goede (1973) used 96 drivers, which does not seem unwieldy.

j. Cost. No production runs have been made for flat-panel CRTs. Production cost estimates suggest the flat-panel CRT will not be competitive with other technologies.

k. Utility for display-type applications. The flat-panel CRT has been shown to meet most requirements for alphanumeric displays, graphics, and television. The flat-panel CRT is not a likely candidate for very large displays, however, because of cost considerations.

l. Future technology projections. At the present time, additional development of the flat-panel CRT technology is hampered by a predicted high cost in production quantities. Although the need for a flat-panel video/graphic capability is generally accepted in the display engineering community, it is also generally thought that other technologies will prove to be more economical.

5.2.4 Light-emitting Diode (LED)

The light-emitting diode (LED) is probably the most widely used and successful form of electroluminescence developed to date. The LED has been used successfully in calculators, wristwatches, instrumentation readouts, and discrete miniature lamps. It has good luminance, low cost, low power, high reliability, and good compatibility with integrated circuit technology. Larger arrays of LEDs have been developed for message readout and graphic displays, although such applications and devices must be considered to be in the development stages.

The LED is a two-terminal semiconductor device that produces visible energy by voltage application to a forward-biased P-N junction. The typical device has a substrate of either gallium phosphide (GaP) or gallium arsenide (GaAs) with GaP leading to greater luminous efficiency because it can be made optically transparent to the LED emission. As the forward voltage is increased, the LED behaves like a classic diode with a sharp knee and then linear current flow roughly proportional to the forward voltage in excess of approximatly 1.5 volts. Figure 120 illustrates this relationship.

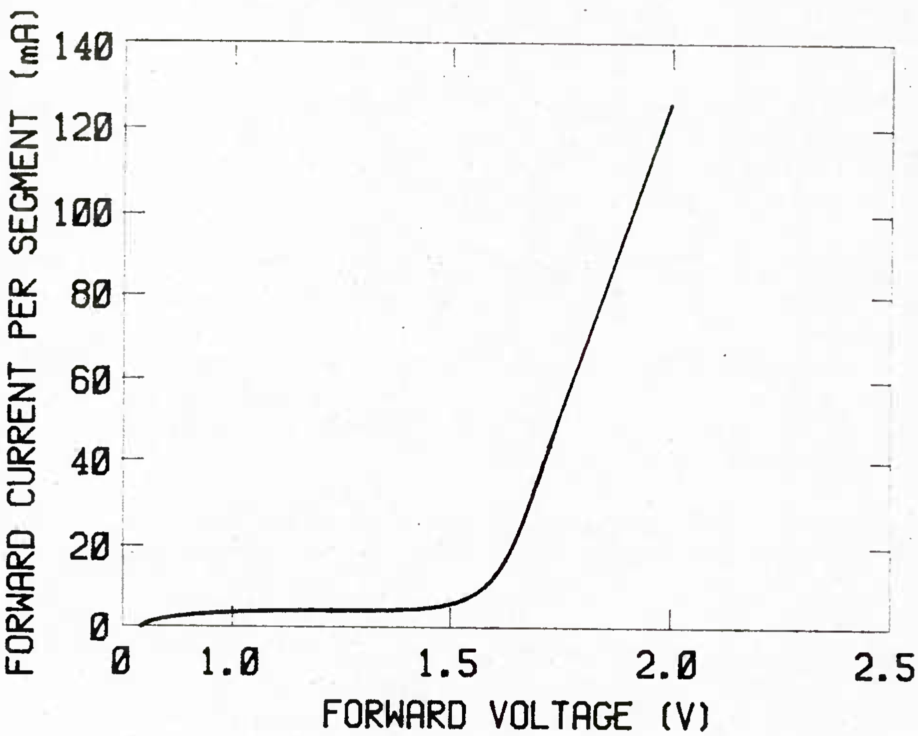


Figure 120. Current-voltage characteristics in forward-bias direction for an LED (taken from Snyder, 1980).

a. Physical size and configuration. A common form of LED is the discrete status (ON-OFF) indicator using a sealed and light-filtered output. In LED numeral readouts, each of the seven segments in the numeral is a separate P-N junction, controlled by external logic and switching circuitry. Larger two-dimensional LED arrays are available in which the LED elements are part of a two-dimensional monolithic pattern, addressed in matrix form by external logic circuitry.

b. Power and voltage requirements. A significant advantage of the LED is its low power consumption and voltage compatibility. Requiring between 1.5 and 5 volts DC, the LED is highly compatible with solid-state circuitry.

Typical requirements are 1 to 5 milliwatts per element for moderate luminance levels. Greater power is required if one wishes increased luminance. For example, a 512 x 512 element array, fully illuminated, would require over 130 amperes of current, an impossible amount in many applications.

c. Spectral emission. LEDs are available in red (655 nm), orange (635 nm), yellow (589 nm), and green (565 nm).

d. Luminance. There is a linear increase in LED luminance with increasing current. As illustrated in Figure 121, the nitrogendoped GaAsP:N/GaP compound is most efficient with its maximum efficiency in the red end of the spectrum, even though the eye is less sensitive to the red wavelengths. Thus, the red LED emits over 65 times as much radiometric energy at 630 nm as it does at 570 nm, more than compensating for the 20:1 loss in visual sensitivity between these two wavelengths.

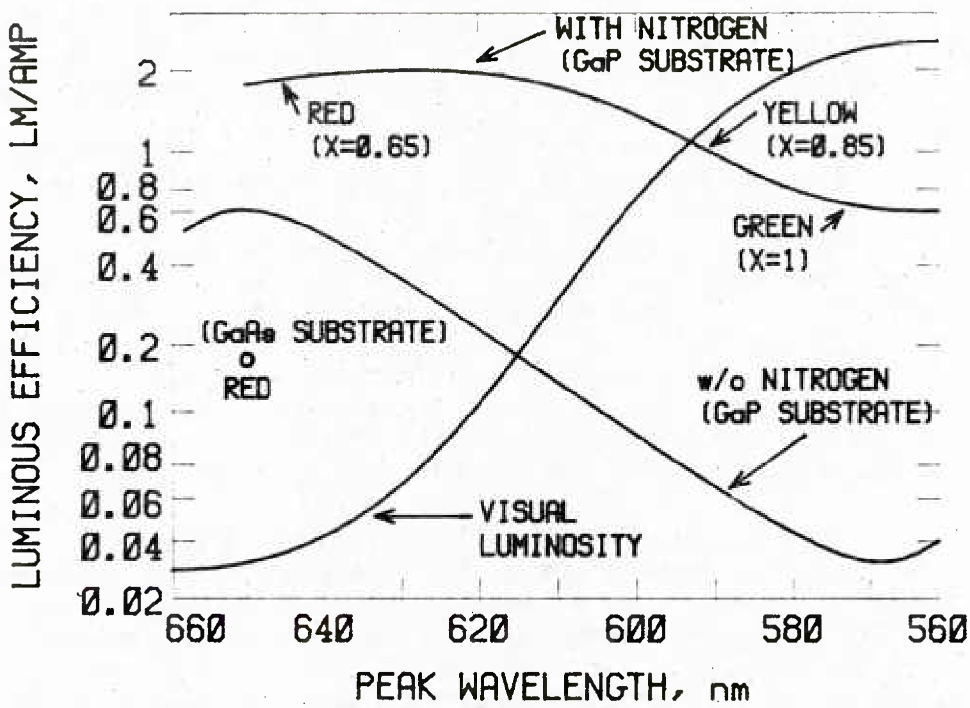


Figure 121. Luminous efficiency of several LEDs (taken from Snyder, 1980).

e. Element size, shape, density. The optical and geometric characteristics of the LED depend considerably on the materials used and the fabrication techniques employed. For these reasons, and because there are many types of LEDs currently in development, it is not possible to define parametric limits for the size, shape, and density of elements in LED arrays.

For discrete element (e.g., OFF-ON) indicators, LEDs are available to a .5 mm diameter or less, and are usually fitted with an integral lens to achieve optical dispersion. The challenge is not, however, in small discrete indicators, but in larger one- and two-dimensional arrays of high density for message readouts, graphic displays, and possibly video presentation. Current technology is adequate for most purposes in achieving small LED element sizes.

f. Contrast and dynamic range. Inadequate information.

g. Uniformity. Discrete LEDs are known to vary in luminance and must be individually tested and grouped when such nonuniformity appears critical. No data on sample variance by LED type are known to exist, however.

LED arrays present the most critical uniformity problem. However, small area nonuniformity due to element outage is not likely to be a major problem in LEDs. For example, a Litton Systems display had only 10 inoperative LEDs out of 49,152 (.02%).

The major problem in LED arrays is to obtain chip-to-chip uniformity. When arrays of 8 x 8 or 30 x 36 LEDs are abutted, edge discontinuities become frequent and are unacceptable for production quality.

h. Temporal characteristics. Although LEDs can be DC driven, high frequency refresh produces much greater luminance and luminous efficiency. What then is the required refresh rate? A refresh rate in the range of 400 to 1000 Hz is needed to avoid flicker or image "breakup." A rate of 500 Hz is acceptable, but a higher rate is required when there is relative motion vibration between the display and the observer.

i. Addressing/driving interfaces. Because of short rise and fall times, the LED has essentially no "memory." As a result, it must be scanned repetitively to maintain high luminance and avoid flicker. Refreshing a 512 x 512 element display at 400 Hz in an element-at-a-time scanning pattern would require an address/refresh rate of slightly over 100 MHz, which is impractical if not impossible. Compared to other technologies, large-array matrix-addressed LED displays appear uneconomical and impractical.

j. Cost. In 1980 small indicator LEDs were available for a few cents, in all four main colors. In large arrays, the cost is estimated at 2.5 cents per element, or about $6500 for a 512 x 512 element array (Scanlan & Carel, 1976). Compared to other alternatives, this cost appears unacceptably high.

k. Utility for display-type applications. LEDs are excellent candidates for single and multiple alphanumeric readouts. They are very inexpensive, draw little power, come in several colors, have a very high luminance (if desired), and can be made into virtually any size or shape. When single LEDs are put into a matrix display for a graphics or television-type image, however, the cost and the power requirements lessen the attractiveness of LEDs. Large screen LED arrays appear to be impractical at the present time.

l. Future technology projections. The display technology is available for high-density LED arrays, but the development (and perhaps production) costs are very high. Coupled with the significant heat dissipation problems of multielement arrays, it appears doubtful that large array LED panels will replace other technologies for graphics and video display requirements.

5.2.5 Electroluminescence (EL)

Electroluminescence has been "around" for many years. The earlier EL displays typically consisted of imbedded phosphor particles in a dielectric medium located between

two parallel conductors or electrodes about 50 microns apart. In more recent developments, the phosphor power is replaced by a film that has been deposited on a substrate, typically glass. Both phosphor power and film layer EL displays can be driven by AC or DC current, thus providing four possible generic types of EL displays.

a. Power and voltage requirements. The voltages driving EL displays generally range from 30 to 650 volts with display luminance directly affected by the driving power. Thus, it is not meaningful to talk about a specific driving voltage for EL displays.

In all cases, operating life decreases as driving voltage increases. Thus, designs that require lower driving voltages are more desirable.

b. Spectral emisison. As with other flat-panel technologies, the emission spectrum of EL varies with the specific chemical material. Copper-activated zinc sulfide (ZnS:Cu) is probably the most commonly used EL power. Depending on the activator concentration, the dominant hue of this compound can range from green to blue. Registered phosphors of ZnS:Cu are the P2 and P31. As the concentrations of silver and copper vary as activators with ZnS, it is possible to obtain any emission hue from red to blue.

c. Luminance. Figure 122 indicates the steady-state luminance of a typical ZnS power when driven at various audio frequencies. Luminance increases with voltage, approximately as the third power. The figure also shows the increase in luminance with the AC frequency, from 400 to 2000 Hz. Some materials reach maximum luminance at 10,000 Hz.

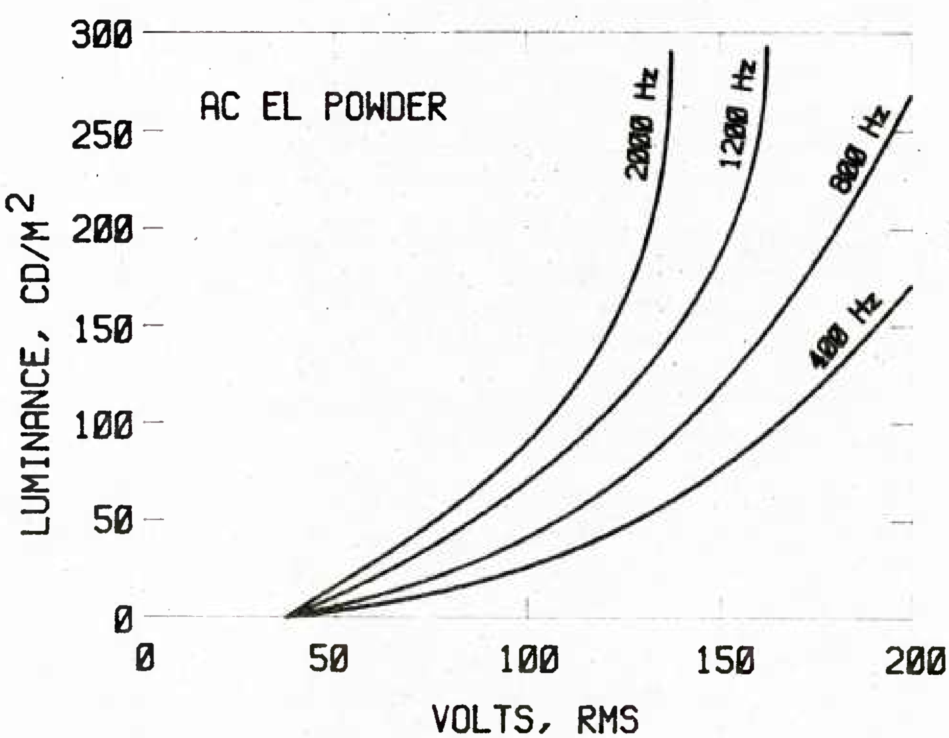


Figure 122. Effect of driving voltage and frequency on EL luminance.

d. Luminous efficiency. According to Kazan (1976), the luminous efficiency of AC power phosphors is about 5 to 10 lm per watt over a considerable range of frequencies for the ZnS greenish-blue emission.

Although DC phosphors achieve high luminances, their luminous efficiency is lower than that of AC phosphors, typically being on the order of .5 lm per watt (Vecht, Werring, Ellis, & Smith, 1973). To date, AC driven thin-film EL displays have had low luminous efficiency, on the order of .3 lm per watt (Kazan, 1976).

e. Element size, shape, density. DC driven EL power displays can be fabricated in a virtually endless combination of sizes and shapes. The element size can be made as small as desirable, limited only by the electrode photofabrication processes. Element sizes as small as 75 x 75 micron are quite achievable (Vecht et al., 1973). Similarly, single areas as great as 800 cm^2 are also commercially available. (Large panels, however, are subject to heat sinking requirements which, if not adequately handled, can cause burn-in nonuniformities.)

f. Contrast and dynamic range. Appropriate selection of driving voltage and EL materials can achieve up to 10^5 cd per m^2 luminance. When coupled with an absorbing background, or a good ambient absorbing filter, a discrete element alphanumeric EL display can provide as much contrast as needed for most applications. For example, the Sharp 48G character alphanumeric display panel has a 25:1 contrast ratio.

Dynamic range and contrast become limited, however, for large matrix-addressed EL displays due to (1) refresh duty cycle, and (2) the "half-brightness" effect. Each of these is important in understanding EL display design tradeoffs.

Because the fall time of the EL element is on the order of 1.5 milliseconds, refresh is necessary, as in the case of the LED. A large matrix, such as 512 x 512, will lead to limited luminance with an element-at-a-time addressing duty cycle or a line-at-a-time addressing duty cycle. At such low duty cycles, high voltages are needed to produce reasonable luminance. Thus, a built-in element electronic circuit is necessary (1) to obtain individual element control without crosstalk or the half-brightness effect, and (2) to provide element-by-element memory, effectively increasing the duty cycle.

g. Uniformity. No quantitative data have been published on the uniformity of EL displays, powder, or film. Assuming fairly even phosphor deposition, one would expect good uniformity when the display is operated at high luminance, for under the high luminance condition the EL element is saturated.

However, many applications (e.g., cockpit displays at night) require uniform dimming, which renders EL less efficient.

h. Temporal characteristics. The rise and fall times of EL phosphors are short enough for many dynamic display applications. For a DC driven ZnS powder at 50 volts, the rise time is approximately 1 millisecond and the fall time is about 1.5 milliseconds.

The average luminance of a DC powder EL panel will depend upon its pulse duration and duty cycle, as well as upon the driving voltage. Dense displays without element memory require high voltage driving to compensate for short duty cycles and short pulse widths.

i. Addressing/driving interfaces. Directly addressed EL alphanumeric segment readouts present no particular interface problems. Although they require voltages in the 50 to 600 volt region, low current power supplies are adequate and driving logic can be interfaced with integrated circuit (IC) electronics.

j. Cost. The cost of EL displays is not dependent on the cost of the phosphor material, for ZnS:Cu can be obtained for about $20 per pound (Schlam, 1973). Rather, the cost is more likely to be driven by the display fabrication process complexity, yield rates, and the associated addressing/memory circuitry.

The electronics cost of a 15- x 15-cm, 512- x 512-element EL panel is estimated to be on the order of $3500 to $5000, in production quantities. To this must be added the production cost of the display panel itself, which simply cannot be estimated at this stage of development of the technology.

k. Utility for display-type applications. The EL display, especially the black layer, thin film EL, is potentially compatible with requirements for alphanumeric readout, graphics, and TV displays, although TFT addressing electronics are probably needed for environments having any significant ambient illuminance.

l. Future technology projections. EL panels have several distinct advantages. They can produce reasonable grey scale and dynamic range, have a wide acceptance angle for viewing, can be fabricated in sizes ranging from a few centimeters to greater than a meter, and are potentially capable of very high element density.

They also have some distinct disadvantages, including the cost of a large number of high voltage drivers, low luminous efficiency, and color limitations.

Applications of thin-film EL technology are growing in number. Flexible alphanumeric readout and graphics capability is already here. Monochrome TV is acceptable, although its subjective yellow color is disliked by many. Color EL TV appears to be far away in the development cycle.

5.2.6 Plasma Displays

The gas discharge, or plasma, display has been produced in large volume, in many configurations and for different applications by several manufacturers. Of all the flat panel technologies, more attention and more success have accompanied the plasma display panel than any other.

There are two types of plasma display, one AC driven and one DC driven. Both have had good success in the market and have been fabricated in alphanumeric readouts as well as in matrix-addressed panels for graphics and alphanumerics.

Plasma displays necessarily have one transparent (front) electrode through which the display is viewed. The rear electrode can be black, reflective, or clear. In the last case, it is possible to rear-project an image on the display, thereby using the plasma display as overlay information on the projected image.

a. Physical size and configuration. Gas discharge or plasma displays have existed for a long time, typified by the well-known Nixie numeric indicator and the common commercial neon sign. The basic mechanism is a gas-filled volume, across which an electrical field can be controlled. The electrical potential can cause an electron to

move from one energy level to a lower energy level, simultaneously separating the electrons from the atoms. When a sufficiently large number of atoms have lost at least one electron, the gas is said to be in its ionized state. Light emission accompanies this process. When the concentration of electrons and ions is less than 1 percent, the gas is called a "plasma," hence the term "plasma display."

In the DC-driven display, the electrodes are located inside the glass plates, in direct contact with the gas-filled center cavities. The AC-driven display, however, has the electrodes separated from the gas. AC- and DC-driven plasma displays are available commercially in a variety of configurations, from 15 to 18 mm to 54 cm square.

b. Power and voltage requirements. Figure 123 illustrates the generalized voltage/current relationship for a DC plasma display. As the voltage is increased, the current flow increases in an accelerating fashion until the ignition threshold voltage (V_s), is reached and no visible glow is present. When the ignition threshold is reached, however, there is a large current increase accompanied by a voltage drop across the electrodes to a minimum (V_e), at which a glow discharge is observed. Lowering the voltage below V_e, the extinction voltage, extinguishes the glow discharge. Thus, if the voltage is held between V_e and V_s, the display can be turned on by applying a pulse that temporarily raises the potential above V_s. Similarly, the emission can be turned off by a temporary pulse that drops the potential below V_e. In essence, the display has "memory" or a storage capability as long as the sustaining voltage is between V_e and V_s.

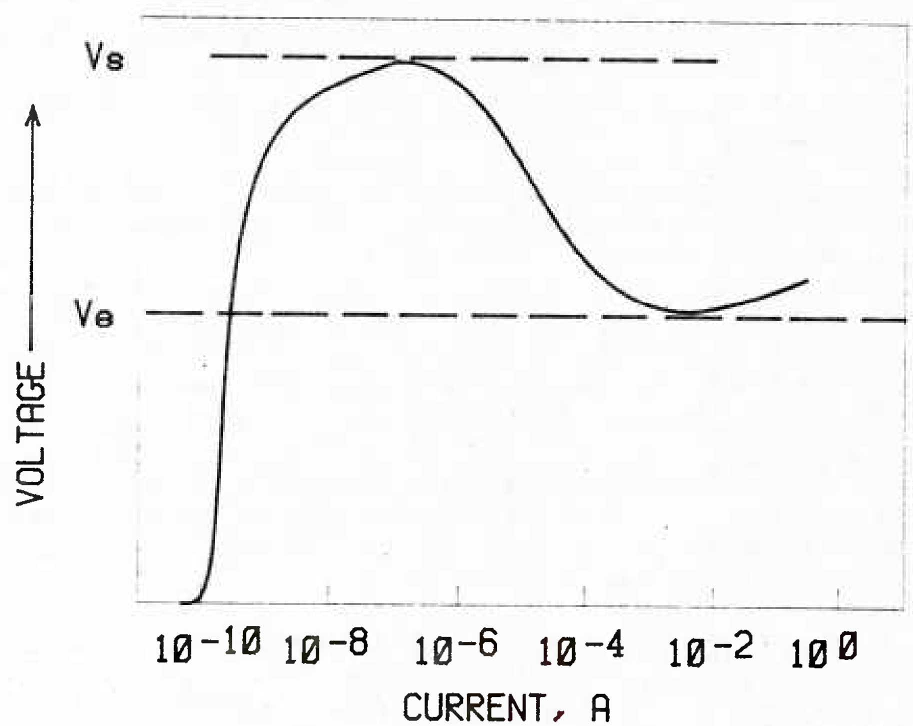


Figure 123. Voltage/current characteristics of a gas discharge display (taken from Snyder, 1980).

c. Spectral emission. The most common emission of plasma displays is orange (585.2 nm) from a neon gas. Other gases, and their discharge colors, which have been used in gas discharge displays, include argon (blue), cadmium (red), helium (yellow), mercury (purple), and sodium (yellow).

Recently, there has been increasing attention to techniques by which multicolor (e.g., television) displays might be obtained with plasma panels. In the most promising technique, the ultraviolet emission of selected neon gas cells excites the phosphor dots in much the same way as the scanning electron beam in a shadow mask CRT selectively excites red, green, and blue phosphor dots.

Thus, it appears that several single gas emission colors are achievable, with different luminous efficiencies. Moreover, by using the ultraviolet gas emission to selectively excite red, green, and blue phosphors, one can obtain a fair coverage of the full color spectrum.

d. Luminance. DC-driven alphanumeric displays are capable of about 150 cd per m^2 to cover 600 cd per m^2, although 30 to 50 cd per m^2 is more typical for long life. DC-driven matrix displays nominally provide about 85 cd per m^2, while the AC-driven provides about 150 cd per m^2 average luminance and 250 cd per m^2 at the peak intensity within the element.

Gas-discharge excited color displays developed thus far are fairly low in luminance, one of the main limitations to wide acceptance.

e. Luminous efficiency. The most common plasma panel has a luminous efficiency of about .3 lm per watt (Crisp, Hinson, & Siegel, 1974). Other orange panel displays have luminous efficiencies ranging from 0.05 to 0.8 lm per watt, while single cell luminous efficiencies have been reported at 1.2 and 3.4 lm per watt (Chodil, 1976).

f. Element size, shape, density. AC-driven panels are now available with up to 1024 x 1024 elements at densities of 2.36, 2.87, and 3.27 elements per mm. Large displays of 54 cm on a side with element densities of 3.94 per mm have also been made.

g. Contrast and dynamic range. DC-driven plasma displays can be controlled in luminance by either current variation or duty-factor modulation. Duty-factor modulation requires constant current but varies the pulse width of each "on" command.

AC-driven displays remain "on" until turned "off." Since they are essentially bistable, two techniques have been developed to control grey levels: spatial modulation and temporal modulation.

In general, contrast ratios from 40:1 to 8:1 have been reported for DC panels (Chodil, 1976), while a ratio of 20:1 is typical for AC plasma displays (Scanlan & Carel, 1976; Sherr, 1979).

h. Uniformity. For existing panels, the manufacturing technology appears to be sufficiently mature to provide good small and large area uniformity (Goede, 1978), although no empirical data are known to exist.

i. Addressing/driving interfaces. An advantage of plasma technology is compatibility with integrated circuit characteristics. Although the sustaining voltages are in the 100 to 300 volt region, the "on" and "off" pulse commands are IC-compatible. Thus, interfacing with computers and other devices is straightforward.

j. Cost. Prices (1980) of 512 x 512 element displays, with all associated driving and addressing electronics, vary from about $4500 for serial input capability to over $9000 for high-speed, parallel processing devices with some internal memory.

k. Utility for display-type applications. Plasma displays have been successfully demonstrated and sold for alphanumeric readouts in single rows, multiple rows, and larger matrix panels. Alphanumeric indicators are available in both dot matrix and seven-segment forms, and lifetimes of 30,000 hours are typical.

Matrix displays ranging from 48 x 65 elements to 512 x 512 elements have been available for graphics and TV applications for several years. More recently, 1024 x 1024 element displays have become commercially available.

It seems unlikely that large-screen displays will become feasible with the plasma discharge technology. Cost and fabrication tolerances would probably cause this technology to be noncompetitive for that application.

5.2.7 Liquid Crystal Displays

The liquid crystal display (LCD) technology is the most popular and most developed of the flat-panel passive display types. Rather than emitting light energy, as do active displays, the passive display controls or modifies the passage of externally generated light.

The liquid crystal material flows like a liquid, but has molecular ordering characteristics of a solid. Thus, the LCD is typically composed of transparent (e.g., glass) plates that sandwich, contain the liquid crystal substance, and also serve as transparent electrodes. Voltages applied to these electrodes cause realignment of the crystal molecules, thereby changing the optical characteristics and light propagation through the liquid crystal substance.

a. Physical size and configuration. The size of an LCD is of course dependent upon the required fabrication techniques. The dynamic scattering mode is the easiest to use for large displays, which have been made 30 cm on a side (Sherr, 1979), since the alignment problem is less critical for dynamic scattering than for twisted nematics.

At the other extreme, the minimum pixel size is limited only by electrode and glass fabrication technology. LCDs with pixels as small as .25 mm have been achieved repeatedly on small (25 mm on a side) panels. Within these limits, there appears to be no serious limitation to the size and shape of LCD elements.

b. Power and voltage requirements. One of the most desirable attributes of the LCD is its very low power requirement. At any voltage or frequency, the current requirement is usually very small, on the order of microamperes so that a small alphanumeric display might operate for a year or two on a battery, drawing only microwatts of power.

Sophisticated instruments having LCD displays can operate long periods on batteries. Further, the voltage and current requirements are easily handled by integrated circuits (ICs), thereby achieving a packaging convenience.

c. Spectral emission. All colors produced except blue are of low to medium saturation. Unfortunately, the dominant wavelength is quite sensitive to temperature changes. For example, at a constant angle of incidence of 30 degrees from the normal, the dominant wavelength ranges from blue to green to red (Scheffer, 1976).

d. Luminance. The luminance of a light modulating transmissive or reflective display is a function of the ambient illuminance and the modulating ability of the display. Therefore, it is not particularly meaningful to consider light modulating LCDs in terms of their luminance characteristics.

e. Luminous efficiency. The concept of luminous efficiency for light modulating displays is, for reasons similar to those of the luminance discussion (above) not particularly meaningful.

f. Element size, shape, density. The element size can be made as small as .254 mm with an interelement space as small as .012 mm, for a percent active area of over 91 percent. Of course, large element sizes are easier to fabricate and elements can be made as large as 5 to 10 mm on a side, if necessary.

g. Contrast and dynamic range. At the present time, contrast ratios of 20:1 to 30:1 are easily obtained, while contrast ratios of nearly 50:1 are possible with careful selection of different front and back polarizers. Sixteen addressable grey levels have been successfully demonstrated.

h. Temporal characteristics. The major limitation to widespread use of LCD displays is the relatively slow response time to either an "on" or an "off" command. Sherr (1979) gives response times of 100 to 500 milliseconds for dynamic scattering LCDs, 100 to 300 milliseconds for twisted nematics, and 50 to 200 milliseconds for DAP LCDs.

While switching rates of 60 Hz have been used for liquid crystal television (LCTV) in keeping with the interlaced broadcast signal, moving objects in LCTV appear blurred and have a "trail."

i. Addressing/driving interfaces. Many of the interface addressing problems of LCDs have been solved, although a large amount of research is still dedicated to the remaining issues in this area.

j. Cost. The LCD has become quite inexpensive because of volume production for use in calculators, wristwatches, and other small units.

k. Utility for display-type applications. The LCD is, for many applications, an ideal choice for single or multiple character alphanumeric readout. The character can be made any size, the contrast is typically adequate, costs are very low, and voltage/power requirements are compatible with battery sources.

Graphic and video displays, on the other hand, are just becoming feasible with LCDs. Matrix addressing remains expensive and complex. Moreover, the contrast sensitivity to voltage and incidence angle variation is a severe limitation to perceptual

uniformity. As a result, applications requiring matrix addressing but only ON/OFF driving (no grey scale) can be considered suitable for LCDs, but grey scale requirements, especially under varying viewing conditions, remain difficult to meet.

Compounding the difficulty for television displays using liquid crystals is the slow response time, leading to significant blur of moving images.

e. Future technology projections. As the demand or potential market increases for matrix addressed LCD panels, the developments required for reasonable production costs should progress. A protytype 500 x 500 element should be available during 1980. Larger sizes are similarly feasible, given the need for such. However, because of addressing complexities, they will probably remain very expensive for the foreseeable future.

5.2.8 Electrochromic Displays

The electrochromic (EC) display is another light modulating display device. It has no light generating or emitting properties; rather, it modulates the ambient (or reflected) illuminance. Compared to the liquid crystal technology, the EC device is generally transparent and absorbs only a selected portion of the visible spectrum upon application of an electric field. The apparent color of the "on" portion of the display is determined by the electrochromic material.

a. Physical size and configuration. The front of the EC cell is a transparent glass plate upon which a thin transparent electrode and the electrochromic film have been deposited. The film is usually backed with an electrolyte, followed by a layer of insulating material, and a back electrode that is usually highly reflective.

This type of EC cell is normally white. However, when a negative voltage is applied to the front (transparent) electrode, the film turns blue and results in a blue-on-white display. Shaping the locations of the EC film controls the element or character shapes. EC displays can be formed in virtually any desired size and shape.

b. Power and voltage requirements. The attractiveness of the EC display is due in large part to its low voltage and power requirements. Change from the white to the color state may be obtained with about 1.5 volts DC and about 5 milliamperes of current. To return from the color state to the white (or transparent) state, the polarity must be reversed and a current of about 15 milliamperes is needed for a short period of time. Thus, the total power used, because of the low duty cycle, is well below that required by LED displays.

c. Spectral emission. Tungsten oxide EC cells, when turned "on," are characterized by a broadband blue color. However, element selection can result in characteristic wavelengths ranging over the entire visible spectrum, although at varying efficiencies.

d. Luminance and luminous efficiency. As with other light modulating display technologies, it is not meaningful to talk about the luminance of the EC device.

e. Element size, shape, density. Theoretically, EC elements can be virtually any size, shape, or density, as limited only by accuracies of film deposition and electrode placement. As a practical matter, however, little attention has been paid to this area of research because the relatively slow response of the EC material precludes its use for

dynamic displays that change more frequently than once or twice per second. Thus, it is incompatible with most graphics and television-type applications.

f. Contrast and dynamic range. As with the LCD, the dynamic range of the EC cell is limited only by the ambient illuminance level. Within this range, luminance modulation of about 90 percent is readily attainable.

g. Uniformity. No data on this point are available.

h. Temporal characteristics. The EC display has inherent memory. Once it is turned "on," the color will remain on for days or until bleached by application of the reversed voltage.

i. Addressing/driving interfaces. There are no commercially available matrix-addressed EC displays. The response time of the EC cell precludes its consideration in matrix displays at the present.

j. Cost. The cost of the EC display should be quite low. The fabrication cost of the EC display would be less than that of the LC display.

k. Utility for display-type application. EC displays have found limited acceptance in alphanumeric display applications, mostly in battery-driven situations such as wristwatches and calculators.

Because of its poorly defined voltage threshold and slow response time, the EC display seems unsuitable for graphics or television-type matrix displays. There have been no attempts to fabricate large-screen EC displays, either real image or projected image, although there appear to be no technological reasons to preclude such a development.

l. Future technology projections. Until the threshold and response time problems are solved, no significant product development is very likely.

5.2.9 Electrophoretic Displays

The electrophoretic induced display (EPID) is also a light modulating, rather than a light emitting, display. It results from the process of electrophoresis, the movement of charged particles suspended in a liquid by the application of an electric field. The pigmented particles are selected to be a different color or optical density than the suspending liquid so that the migration to the front surface of the display cell permits the observer to "see" the particles, whereas migration to the rear surface of the display causes the observer to see only the suspending liquid.

a. Physical size and configuration. Like many other solid-state displays, EPID is essentially a transparent sandwich, with the front and rear plates coated with conducting electrodes. The cavity created by spacers between the two transparent electrodes is filled with a fluid composed of a small pigmented particle suspension in a dense liquid. Application of an electric field across the electrodes causes the particles to migrate toward one or the other electrode.

b. Power and voltage requirements. Operating voltages explored thus far have ranged from ± 2.5 to ± 100 volts DC. A representative optimal voltage would be about 40 volts DC for a pigment (particle) concentration of 30 mg per ml and a dye concentration of 4 mg per ml.

c. Spectral emission. EPIDs can be fabricated in a variety of color combinations, ranging from black/white to blue/white, black/yellow, red/yellow. Other combinations are possible, depending only on the particle and dye choices.

d. Luminance. As with other light modulating display technologies, display luminance is a function of the ambient illuminance and the light attenuation of the display. EPIDs are easily legible at illumination levels of 10 lux; legibility improves up to 10^5 lux.

e. Luminous efficiency. Luminous efficiency is an inappropriate measure for the EPID.

f. Element size, shape, density. The size, shape, and density of EPID elements is limited by the accuracy of electrode placement and cell construction. There seem to be no problems fabricating large cells up to 150 x 300 mm (Ota et al., 1975) or as dense as 5 elements per mm (Dalisa, 1977).

g. Contrast and dynamic range. The dynamic range of an EPID cell depends on the ambient illuminance and the optical transmission through the display. There is an optimal voltage for combinations of dye and pigment concentration. Similarly, the contrast ratio varies with EPID cell thickness and applied voltage. Contrast ratios up to 7 or 7.5 appear reasonable.

h. Uniformity. No data have been reported on the uniformity of EPID cells. However, uniformity should not be a significant problem.

i. Temporal characteristics. EPID may retain an image up to several months after the voltage is removed (i.e., it has intrinsic memory as long as the viscosities and densities of the dye and particle portions are comparable).

j. Addressing/driving interfaces. EPID has a fairly stable threshold voltage, such that there is adequate discrimination for use in matrix displays.

k. Cost. EPID technology is too new to estimate production costs. However, the simplicity of construction and the relatively low material cost suggest that EPIDs, in production, should cost on the same order as EC displays.

l. Utility for display-type applications. Laboratory prototypes have demonstrated the feasibility of EPIDs for on-off displays, seven-segment alphanumerics, and matrix displays. While these are all feasible, the application of EPID matrix displays to dynamic content, such as television, is probably precluded by the response speed (e.g., 50 to 100 milliseconds) of the device. Similarly, applications involving large screen displays are possible if matrix addressing and cost are not limitations.

In general, EPID displays are aesthetically pleasing, due in part to the color combinations available to the designer. They have a very wide, useful, viewing angle, estimated to approach ± 90 degrees; thus, there is potential application for multiviewer large-screen EPIDs.

m. Future technology projections. The EPID is too new to project its utility very far into the future.

5.3 Display Technology Comparisons

Tables 29 through 41 compare these new display technologies in the 13 categories on which they were previously compared. Comparable data for the CRT are also given in these tables.

To date, large displays (e.g., .5 m or more on a side) have only been made in CRTs, EL panels, and plasma panels. Conceivably, LED arrays and LCDs that large could be fabricated but none are presently known to exist. Thus, if the application calls for a display larger than .5 m on a side, the designer is restricted to CRTs, EL panels, and plasma panels. On the other hand, if display depth is a problem or limitation, as in some vehicular installations, then the CRT might be eliminated.

Secondly, some applications will be limited in terms of power and voltage requirements. CRTs require high voltages and draw a fairly large amount of power. Thus, for an application requiring both large displays and low power, the EL and plasma panels become most attractive. For smaller displays, EC and EPID displays offer attractively lower power consumption as long as the application requires only alphanumeric readouts; for these technologies, matrix and TV capabilities have yet to be proven.

Table 29

Comparison of Physical Size and Configuration Characteristics of the Display Technologies

Display Type	Display Size	Display Depth	Construction	Yield (in prod.)
CRT	0.75 m, diag.	$\geq$ 1.2 x display diag.	not apprec.	high, exc. for blemish free
Flat-panel CRT	(16.26 cm)^2	1.5 cm	not apprec.	unknown
LED	(0.26 m)^2 to date	$\approx$ 10 mm	not apprec.	high
EL	(1.63 m)^2	$\approx$ 5 mm	not diff.	high
Plasma Discharge	(54 cm)^2	$\approx$ 12 mm	not apprec.	high, now mature technology
LC	(30 cm)^2	1-2 mm	not apprec.	high
EC	no known limits	1-2 mm	not diff.	high
EPID	150 x 300 mm to date	1-2 mm	not apprec.	unknown

Table 30

Comparison of Power and Voltage Requirements Characteristics of the Display Technologies

Display Type	Voltage Requirements (V)	Power Consumption	Other
CRT	several, to 15 KV	$\geq$ 100 W	several voltages, complex
Flat-panel CRT	20-30 VDC	100 mW/cm^2	none
LED	1.5-5.0 DC	1-5 mW/element, typ.	none
EL	30-650 AC	2-6 mA/cm^2	none
Plasma discharge	200 DC or 200 AC	400-500 mW/cm^2	none
LC	1-8, DC	1 mW/cm^2	none
EC	1.5 DC	100 mW/cm^2	none
EPID	2.5-100 DC	0.3 mW/cm^2	none

Table 31

Comparison of Spectral Emission Characteristics of the Display Technologies

Display Type	Dominant Wavelength	Spectral Dispersion	No. of Discriminable Colors Available
CRT	Varies with phosphor	Varies with phosphor	$\leq$ 20 with 3-gun CRT
Flat-panel CRT	Varies with phosphor	Varies with phosphor	$\leq$ 20 with triad dots
LED	649, 632, 590, 550, 470 nm	red, orange, yellow blue, green (wide, continuous)	5
EL	525, 585 nm; varies with phosphor	100 nm	2-3
Plasma discharge	585 nm (neon) others less common	Varies with phosphor or gas	$\leq$ 20 with full color; 1 otherwise
LC	varied	narrow	unknown
EC	varied	varied	unknown
EPID	varied	unknown	unknown

Table 32

Comparison of Luminance Characteristics of the Display Technologies

Display Type	Max. Luminance (cd per m^2)	Min. Luminance (cd per m^2)	Dependent on Resolution
CRT	$\approx$ 30,000 300 typical	1-2	yes
Flat-panel CRT	820	1-2	yes
LED	68,500	0	no
EL	10,000	0	no
Plasma discharge	600	0	no
LC	n/a	n/a	no
EC	n/a	n/a	no
EPID	n/a	n/a	no

Table 33

Comparison of Luminous Efficiency Characteristics of the Display Technologies

Display Type	Lumens/Watt, Maximum	Lumens/Watt, Minimum
CRT	65, P20	0.1, P16
Flat-panel CRT	2 (est.)	unknown
LED	4.2 (green)	0.006 (yellow)
EL	19	0.3 (AC)
Plasma discharge	3.4	0.05 to 0.3 (typical)
LC	n/a	n/a
EC	n/a	n/a
EPID	n/a	n/a

Table 34

Comparison of Element Size, Shape, and Density Characteristics of the Display Technologies

Display Type	Element Size, Minimum, mm	Element Shape(s)	Element Density	Max. Matrix Size Fabricated to Date
CRT	0.07 at 2.35 σ	Gaussian	variable	0.75 m, diag.
Flat-panel CRT	0.35 (est.)	Gaussian	to 3.15 mm	$(16.26\ cm)^2$
LED	0.08	round, square	to 10/mm	$(204\ mm)^2$
EL	0.05	selectable	to 19/mm	$(15\ cm)^2$
Plasma discharge	0.25	double diamond	to 3.27/mm	$(54\ cm)^2$
LC	0.254	selectable	to 3.93/mm	$(89\ mm)^2$
EC	unknown	selectable	unknown	n/a
EPID	unknown	selectable	to 5/mm	n/a

Table 35

Comparison of Contrast and Dynamic Range Characteristics of the Display Technologies

Display Type	Maximum Modulation	Dependent on Ambient Illuminance	Light Emitter or Light Modulator
CRT	98%, at low luminance and low ambient	yes	emitter
Flat-panel CRT	98%	yes	emitter
LED	96%	somewhat	emitter
EL	92%	somewhat	emitter
Plasma discharge	95%	somewhat	emitter
LC	96%	yes	modulator
EC	90%	yes	modulator
EPID	94%	yes	modulator

Table 36

Comparison of Uniformity Characteristics of the Display Technologies

Display Type	Small Area	Large Area	Image Geometric Stability
CRT	good	fair, 50% rolloff	fair
Flat-panel CRT	fair	fair to good	good
LED	good	large-area nonuniformity	very good
EL	fair	fair	very good
Plasma discharge	good	good	very good
LC	good	fair	very good
EC	probably good	unknown	very good
EPID	probably good	unknown	very good

Table 37

Comparison of Temporal Characteristics of the Display Technology

Display Type	Rise Time	Fall Time	Inherent Memory	Refresh Requirements
CRT	1 μs to > 1 ms, depend on phosphor	1 s to > 100 ms, depend on phosphor	typically not, except for storage CRTs	varies with phosphor
Flat-panel CRT	same as CRT	same as CRT	same as CRT	same as CRT
LED	10 ns	10 ns	none	very high, 500 Hz typ.
EL	1 ms	10 μs to 1.5 ms	no	60 Hz
Plasma discharge	100 ns	2 μs	yes	50-60 Hz
LC	50-300 ms	100-400 ms	yes	none
EC	0.1-1.0 s	0.1-1.0 s	yes	none
EPID	10-100 ms	10-100 ms	yes	none

Table 38

Comparison of Addressing/Driving Interface Characteristics of the Display Technologies

Display Type	Defined Threshold	High Voltage Requirements	Element Drivers Necessary	Matrix Compatible
CRT	no, analog driven	12-15 KV	no	yes
Flat-panel CRT	no, analog driven	no	no	yes, but not X-Y directly
LED	yes	no	no	no, very high refresh rate needed
EL	yes	yes, 50-600	typically	yes
Plasma discharge	yes, very	no	no	yes
LC	unstable	no	usually	yes
EC	not very	no	n/a	no
EPID	yes, stable	no	probably not	probably

Table 39

Comparison of Cost Characteristics of the Display Technologies

Display Type	Known or Estimated	Production Quantity Estimate
CRT	known	<\$10 for monochrome; <\$100 for color
Flat-panel CRT	estimated	high, major problem
LED	known	4-8¢/element singly: \$6500 for $(512)^2$ array
EL	known	\$3500 to \$5000 for $(512)^2$
Plasma discharge	known	\$4000 to \$9500 for $(512)^2$
LC	known/estimated	\$15/TV panel; \$150 for TV system
EC	estimated	low
EPID	estimated	low

Table 40

Comparison of Utility for Display Technologies

Display Type	Single Alphanumeric	Matrix (Graphic)	Matrix (TV)	Large-screen, Direct Viewing	Large-screen, Projection	Grey Scale Available
CRT	possible, but not practical	yes	yes	yes, but low luminance	yes, with light valve	yes
Flat-panel CRT	yes	yes	yes	no	no	yes
LED	yes	available, but too expensive	no, too costly	no	no	yes
EL	yes	yes	monochrome only	no	no	yes
Plasma Discharge	yes	yes	yes	no	no	yes
LC	yes	yes	yes	no	yes, as light valve	yes
EC	yes	no	no	no	no	no
EPID	yes	perhaps	doubtful	potentially yes	unlikely	yes

Table 41

Comparison of Future Technology Projections of the Display Technologies

Display Type	Mature Technology	Major Improvements Likely	Major Improvements Required for Widespread Usage
CRT	very	minor only	none
Flat-panel CRT	no	possible	cost, color
LED	yes	unlikely	cost and uniformity
EL	moderately	yes	cost, luminous efficiency
Plasma discharge	yes	yes	cost, color
LC	moderately	yes	rise/fall times, angular viewing
EC	no	perhaps	response times, threshold
EPID	no	yes	response times, addressing

Color displays are available with several technologies, but full color control at nonflickering rates is still best achieved with CRTs, although plasma displays will provide a challenge for those applications in which low luminance is acceptable.

Under high ambient conditions and for monochromatic displays, acceptable candidates are CRTs, LEDs, and ELs. Under some circumstances, light modulating displays will provide the greatest contrast, since their contrast generally increases with increasing ambient illuminance. However, under low ambient illuminance, light modulating displays require an internal illuminance source. High luminance displays that have resolution that varies with the luminance level at which they are driven, such as the CRT, must be selected carefully. Displays that have fixed element geometry, however, can successfully be luminance-modulated with no effect on element density or resolution. Solid state displays fall into this category, although the only flat-panel display that has a luminous efficiency reasonably close to the CRT is the EL panel.

If high resolution is demanded for a given application, then attention should be given to LEDs, ELs, and CRTs. Again, however, the EL and LED element sizes are invariant with luminance level, while the CRT small spot size will bloom with luminance increases.

All technologies are capable of good dynamic range under ideal illuminance conditions, but some (e.g., CRT, LED, EL, and plasma) achieve this high modulation under low illuminance, while others (e.g., LC, EC, and EPID) achieve it under high illuminance. Care must be taken, then, to consider carefully the operating ambient.

While uniformity requirements of the human observer are not well substantiated, one does find large variability in uniformity among the technologies surveyed. At the present time, in the absence of justifiable criteria for the three types of uniformity, the designer can only use good judgment in applying this criterion to device selection.

Some technologies are clearly fast reacting, and thereby permit rapid change of displayed information. These include CRTs, ELs, plasma panels, and LEDs. In fact, the LED rise and fall times are so short that they cause significant refresh problems. On the other hand, if the information change rate is relatively slow and especially if only small amounts of alphanumeric data are to be displayed, using LC, EC, or EPID displays greatly simplifies refresh problems.

Some technologies are much more compatible with addressing and driving flexibility than are others. For example, CRTs are relatively easily driven in stroke, vector, or raster modes, and the techniques are well defined and proven. LEDs, on the other hand, because of their very short rise/fall time, are virtually impossible to use in a large matrix display. EL, plasma, and LC displays have been successfully used in matrix displays for both vectorgraphics and TV applications. Further improvements are likely in each of these latter three technologies for matrix use.

Costs of these technologies vary considerably, ranging from very small amounts for EC, LC, LED, and EPID alphanumeric readouts, to large amounts for LED, EL, and plasma matrix displays. At the present time, the CRT is by far the cheapest and most flexible of the matrix display types, offering inexpensive display of alphanumerics, graphics, and TV. While some displays have been sold in large quantities in a direct competition against the CRT, their costs have not been competitive.

The only technologies showing current capability or near-term promise for large-screen projection displays are the projection or light-valve CRT and the liquid crystal light valve. Large-screen direct viewing displays are likely to be limited to CRTs and EPIDs in the near future, with EPIDs having only monochrome capabilities.

5.4 Flat Panel Display Resolution

5.4.1 Effect of Element Shape on Operator Performance

The resolution or density of the fixed element (or pixel) flat panel display is determined by the element size, element shape, and element edge-to-edge spacing. Unlike the CRT, changes in flat panel image content have no appreciable effect on element density. The element density of flat panel displays is essentially invariant everywhere on the display, whereas the resolution of the CRT varies with display position, luminance, focus, and a few other parameters.

It makes more sense then to relate observer performance to flat-panel element density (element size, shape, and spacing). Snyder and Maddox (1978) found that the square element shape is better than an elongated element shape for either reading or search (Figures 124 and 125). Further, when replicated using Self-Scan panels having either square or round elements, the square elements proved superior for both reading and search. Thus, the existing data support the conclusion that the more square the display element is, the better the observer's performance.

Optimization of element size is a complex problem. For reading tasks, as with alphanumeric paragraphs, it is possible to make the element too large, as shown in Figure 126. For search tasks, however, large elements lead to more rapid identification of symbols and characters (Figure 127). Apparently, reading efficiency is obtained by using smaller, compact characters that minimize the number of eye fixations, whereas search, a task requiring detection in the visual periphery, requires larger elements (and, hence, larger characters). Certainly, these generalizations can be over-extended, but within the .75- to -1.50 mm element size, they appear consistent.

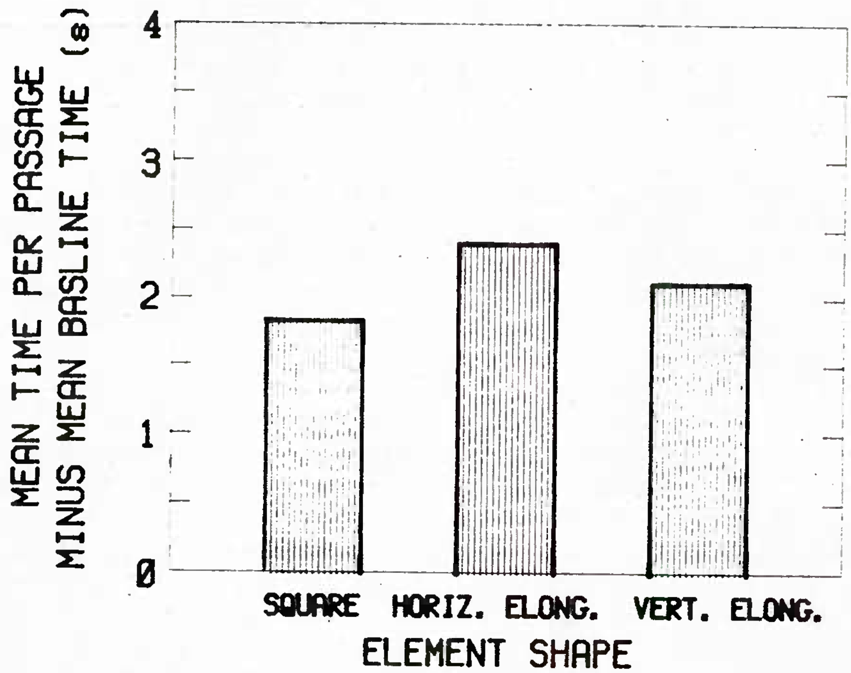


Figure 124. Effect of element shape on reading time (from Snyder & Maddox, 1978).

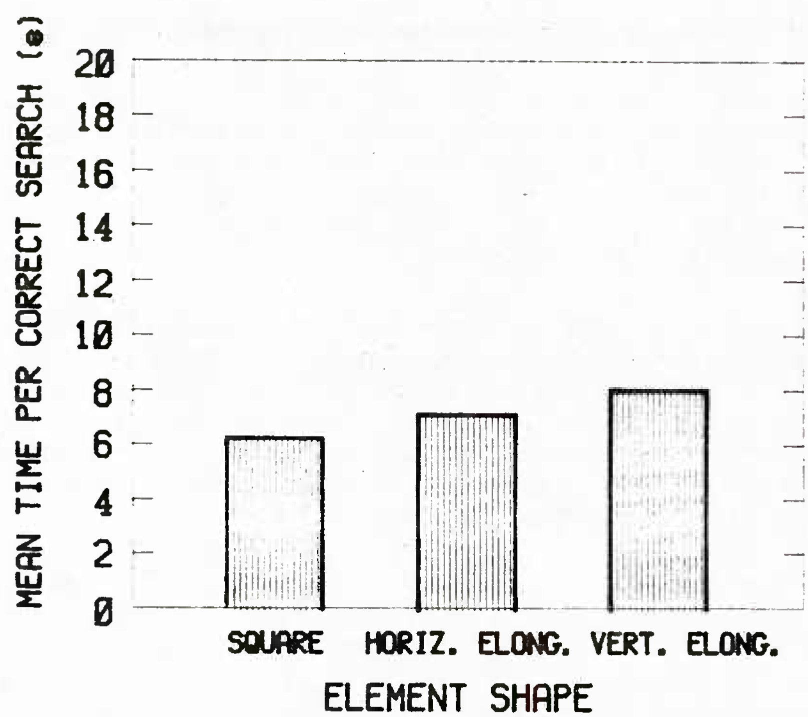


Figure 125. Effect of element shape upon random search time (from Snyder & Maddox, 1978).

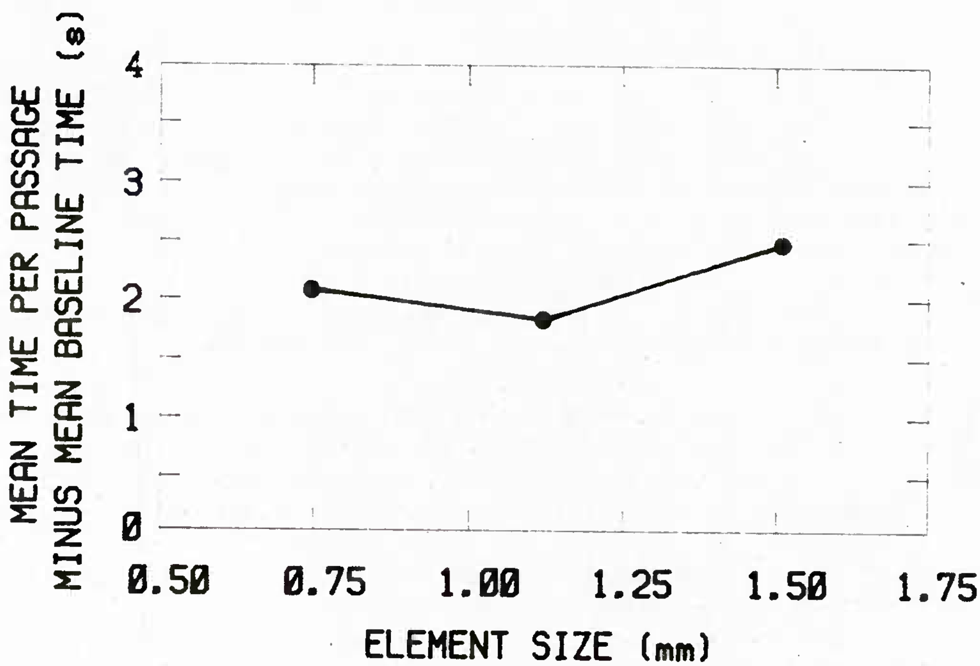


Figure 126. Effect of element size on reading time (from Snyder & Maddox, 1978).

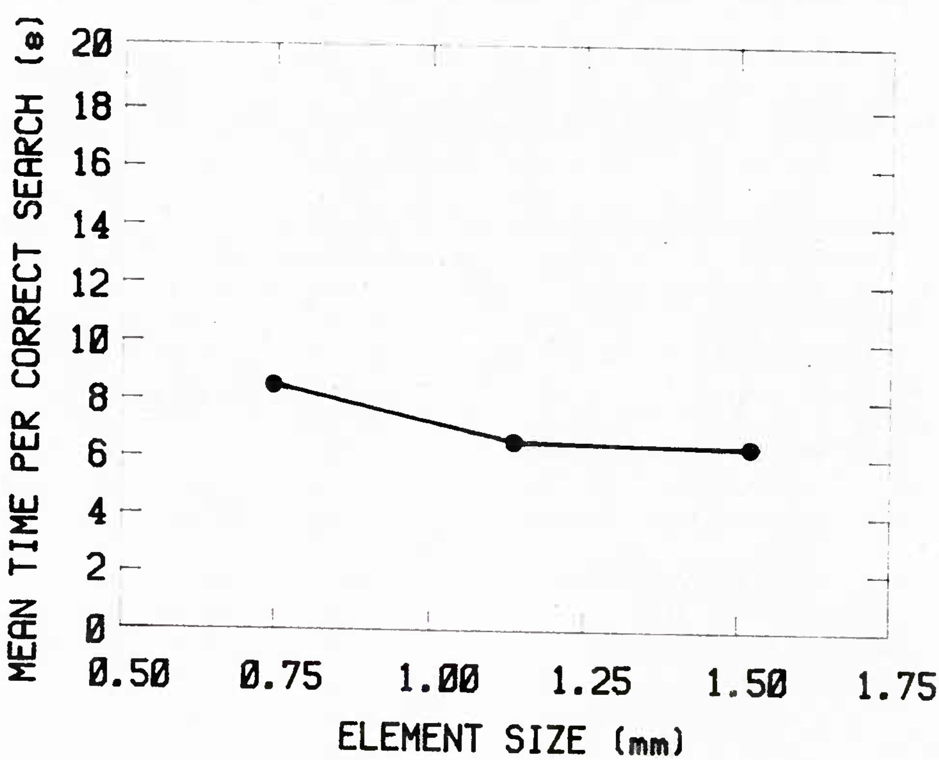


Figure 127. Effect of element size on random search time (from Snyder & Maddox, 1978).

5.4.2 Effect of Element Spacing and Continuity on Operator Performance

Several studies have demonstrated that the closer a dot-matrix stroke or line approximates a solid line, the better is the legibility and readability. Vanderkolk, Herman, and Hershberger (1975) showed that performance improves as the percent active area increases. More recently, Stein (1980) found that percent active area is not related to character recognition performance under good viewing conditions, but that under "stressed" conditions (decreased contrast, increased reading distance) performance fell off precipitously as percent active area fell below 45 percent (Figure 128). Similarly, Snyder and Maddox (1978) found a correlation between percent active area and reading time of $r = -.77$ ($p < .0001$), between percent active area and menu search time $r = -.53$ ($p = .004$), and between percent active area and random search time $r = -.30$ ($p < .05$).

The effect of percent active area is clearly not linear, as shown by Figure 128. In fact, it is probably best interpreted as the ratio of the element size to the between-element spacing. As this ratio increases, the line begins to appear more continuous, and the alphanumeric character is more easily read or found, as illustrated in Figure 129.

This is in keeping with what is known about raster line visibility in line-scan displays (e.g., television) and suggests that inter-element spacing should be no more than 50 percent of the element width (44% active area) and preferably much less. Not all matrix element technologies currently meet that criterion.

5.4.3 Effects of Size and Scale on Operator Performance

For a fixed element size, increasing the display size can be beneficial because it permits the presentation of more information, at an increase in cost.

If the element size is scaled up with increases in display size, there is a maximum beyond which decreasing performance results; this maximum occurs when the individual elements become visible. Elements are visible when they exceed the visual contrast sensitivity threshold, which depends upon spatial frequency and modulation.

If displayed information is scaled up with display size, benefits can be obtained as the spatial frequency of the information approaches the most sensitive spatial frequency range of the visual system for the given viewing conditions. This latter point is critical to good display design. For example, if a 10-cm wide display contains image information that has most of its power at 20 cycles per degree, scaling the display size to 25 cm will decrease the spatial frequency of the image, at maximum power, to 8 cycles per degree, which is nearer the peak of the visual contrast sensitivity function, thus making the image content more visible. However, if the unmodulated element spatial frequency, which is actually a static noise source to the visual system, also becomes proportionally more prominent by this scaling, nothing is gained.

One way to evaluate optimum display size is to consider the inverse of the contrast sensitivity function as a figure of merit. Figure 130 indicates that optimum display size varies with the viewing distance to keep the target (or displayed information) spatial frequency in the most sensitive region of the "figure of merit" curve. Changes in display luminance, target spatial frequency, element spatial frequency, etc. would alter the position of these figure of merit curves.

	UNSTRESSED CONDITION A	DECREASED LUMINANCE CONDITION B	DECREASED LUMINANCE & INCREASED READING DIST CONDITION C	DECREASED CONTRAST & INCREASED READING DIST CONDITION D
BACKGROUND (fL) LUMINANCE	1.2	0.12	0.12	0.97
READING DIST (INCHES)	18	18	24	24
CONTRAST	75	75	75	32

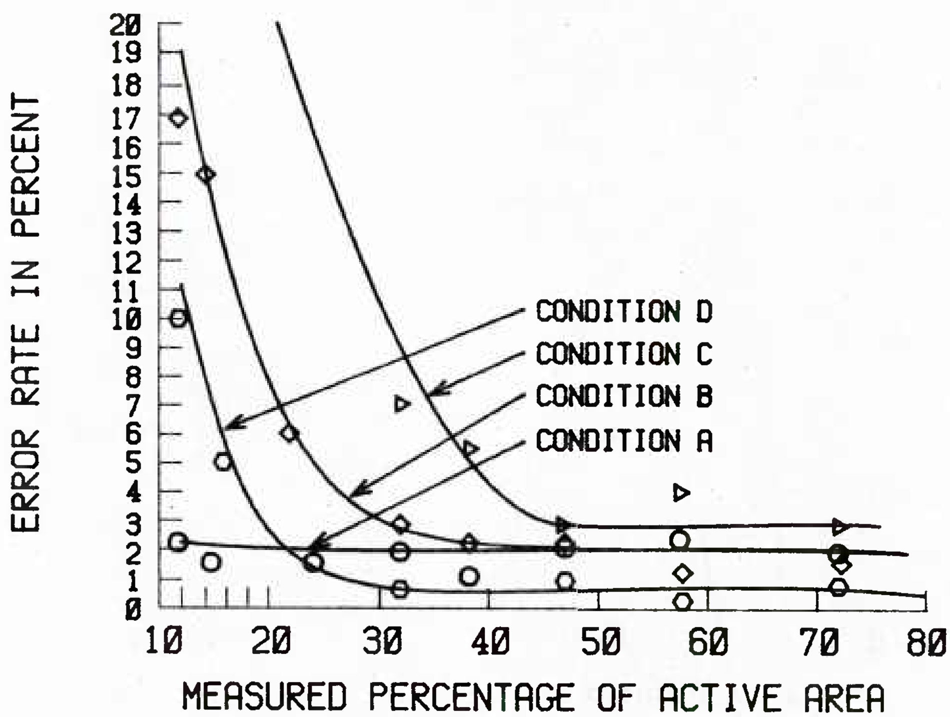


Figure 128. Effect of percent active area on character recognition (from Stein, 1980).

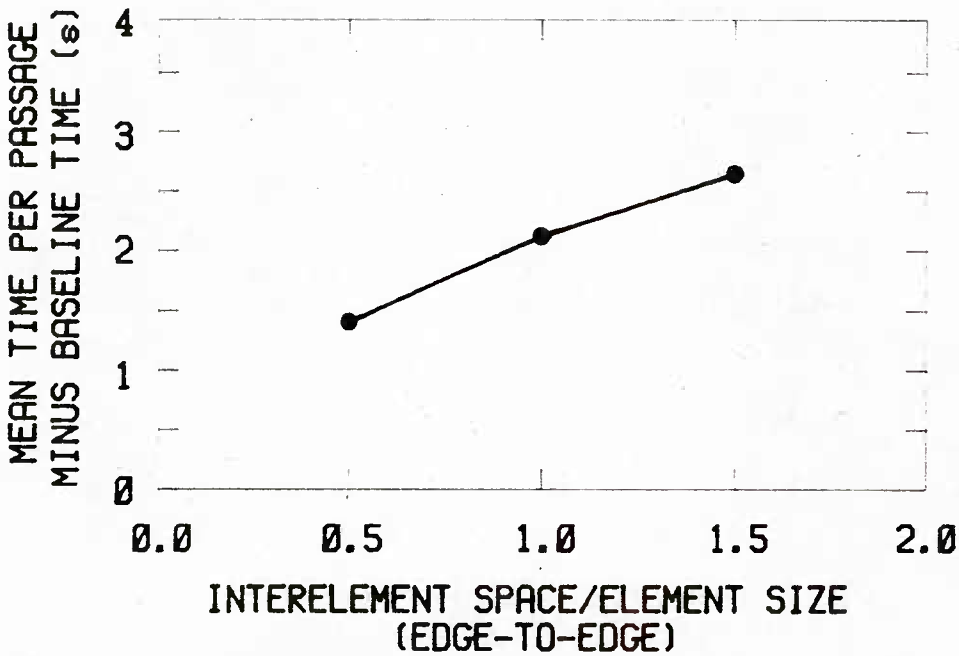


Figure 129. Effect of element size to element spacing ratio on reading time (from Snyder & Maddox, 1978).

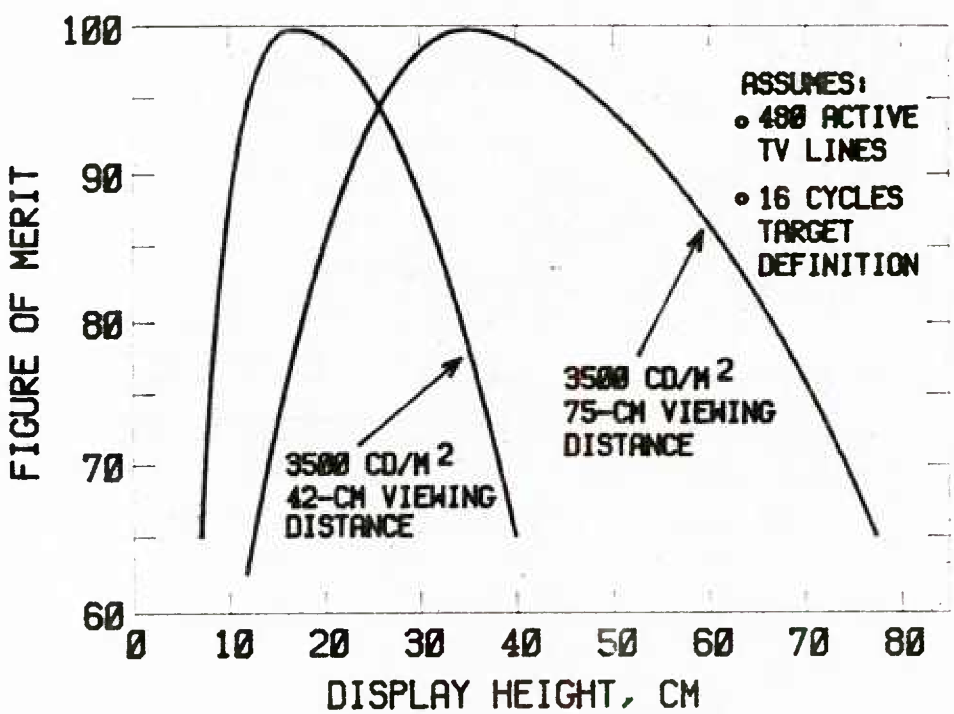


Figure 130. Figure of merit for display size for two viewing distances (from Carel, Herman, & Hershberger, 1976).

SECTION 6

TARGET ACQUISITION IMAGING SYSTEMS

6.0 TARGET ACQUISITON IMAGING SYSTEMS

6.1 Introduction

Target acquisition imaging systems include low light level TV (LLLTV), infrared (IR) scanners, and laser scanners. These systems are used primarily for display of data acquired through special sensor channels and for identification and tracking of objects. They are not used for processing of information whose characteristics (e.g., alphanumerics) are known, where standard TV and computer CRT displays are used. Of course, some of the material discussed in this section will overlap with material applied to other types of displays, but the distinctive nature of the systems and situations in which they are used warrant special discussion. Much of this material has been taken from Jones, Freitag, and Collyer (1974) to which the reader should refer for more detailed discussion.

6.2 Field of View (FOV)

6.2.1 Selection Considerations

The choice of optimal sensor field of view (FOV) is extremely important. Factors to be considered in this selection include anticipated altitude (in air-to-ground target acquisition); speed, type, and size of target searched for; type of terrain being searched; and the nature of the mission.

No single specification of the best FOV, even for a specific set of target/environmental conditions, can be given because of the tradeoffs required.

a. A wide FOV permits a greater amount of ground to be covered and thus increases the probability that targets will be picked up by the observer. However, target images become smaller as FOV increases.

b. The targets' displayed size, however, may be such that recognition is not possible at a reasonable operational range.

c. A smaller FOV, hence greater magnification, can result in increased recognition slant ranges, but at the expense of a greater number of missed (not displayed) targets. On the other hand, Wagner (1975) found that with a smaller FOV (3.25 degrees compared to 4.5 degrees or 52% as much terrain) correct detections (at a simulated altitude of 1220 meters) more than doubled (86% from 41%). When FOV is decreased, targets are less likely to be displayed but more likely to be detected if they do appear.

d. Differences in FOV also affect the displayed velocity of the target, as well as the target dwell time on the display. With a wide FOV, angular rates of the target across the display are decreased, which facilitate performance. The amount of time the target appears on the display is also increased.

e. On the other hand, a wide FOV displays more false targets and increases the observer's search requirements.

f. If the system is to be used for navigation as well as for target acquisition, a wide FOV is preferable to a relatively narrow one (e.g., Leininger et al., 1963; Williams, Borda, & Larue, 1965; and Kinder, Stedman, & Holt, 1970).

Figure 131 shows the effect of camera field of view on target recognition performance (Rusis & Snyder, 1965). For example, 10 percent of the targets can be recognized at about twice the slant range for the smallest FOV as compared with the largest FOV. On the other hand, only about 55 percent of the targets were ever recognized with the narrow FOV, as compared to almost 90 percent with the largest FOV.

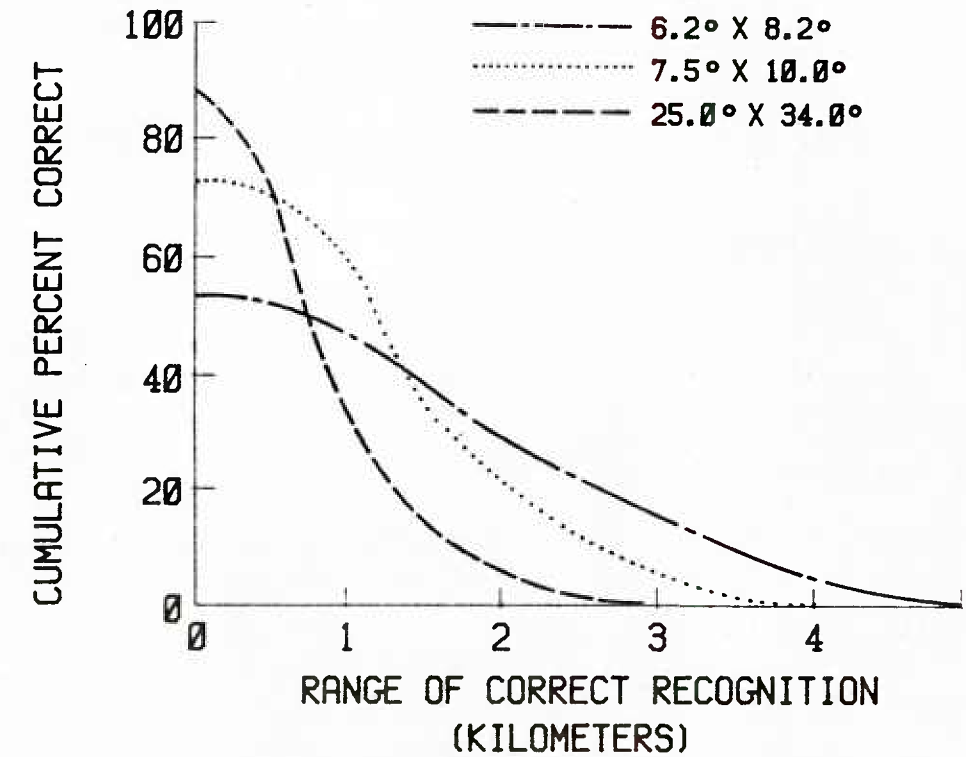


Figure 131. The effect of camera field of view on target recognition performance (from Rusis & Snyder, 1965).

Wyman, Rawlings, and Sturm (1966) found that, as horizontal FOV decreased from 50 to 20 degrees, the mean range for correct recognition increased from 5200 to 10,500 feet, while total target recognition probability decreased from .68 to .52. Humes and Bauerschmidt (1968) found much the same thing.

It appears then that the choice of FOV depends in part on the nature of the mission and the number of targets anticipated. On a mission where targets are plentiful and detection at long range is necessary to achieve a high kill probability, a relatively narrow FOV is indicated. If it is important to allow few if any targets to go undetected, a wider FOV is appropriate, provided target images retain adequate size and resolution. Too narrow or wide FOV both yield fewer targets detected; in the first instance, they never appear on the display and in the second, they appear, but are too small to be detected and recognized.

Since each FOV has both advantages and drawbacks, it is recommended that, where possible, variable FOVs be employed. One possibility is a zoom lens, but this requires frequent adjustments and loss of resolution while the FOV is changing. Moreover, zooms faster than f/1 (for IR or LLLTV) are not as yet technically feasible.

Another possibility is a dual FOV. In one study (Carter, 1962) with LLLTV, all operators preferred a wide FOV for search with a switch to a narrow FOV for recognition. Wyman and Sturm (1966) studied a dual TV system with a wide (28 degrees horizontal) and narrow (5 degrees) FOV scene presented simultaneously. The observer could select the portion of the wide FOV to magnify. In comparison with a fixed wide-FOV system, the dual system reduced recognition time significantly but recognition probabilities were not affected, since a wide FOV improves target recognition anyway.

6.2.2 Ways of Determining Required FOV

Assuming a target is within the FOV, it is important for the system designer to know the minimum amount of magnification that is necessary to detect, recognize, orient, and identify the target. Definitions of these terms are as follows:

a. Detection. An object is present.

b. Orientation. The object is approximately symmetric or asymmetric and its orientation can be determined.

c. Recognition. The class to which the object belongs may be discerned (e.g., surface ship, submarine, destroyer, etc.).

d. Identification. The target can be described to the limit of the observer's knowledge (e.g., 963 class destroyer, Golf-type submarine, etc.).

Several variables affect the required amount of magnification: Total system resolution; FOV; target size; distance from the target; number of resolution lines required across the target. Designers would wish to solve either for maximum permissible FOV or minimum required system resolution.

The maximum FOV at which a particular operation could be carried out is approximated by the following formula (for angles up to 6 degrees):

$$FOV = \frac{L \times 57.3}{R} \cdot \frac{T}{n} , \tag{6.1}$$

where

FOV = field of view (in degrees),
L = total system line number (a measure of system resolution, expressed as a number of TV lines per picture height),
R = range to target (in meters),
n = required number of TV lines across the minimum dimension of the target,
T = target size across minimum dimension (in m).

The formula for minimum system resolution (L) required for target acquisition when a particular FOV is assumed is:

$$L = \frac{FOV \cdot R}{57.3} \cdot \frac{n}{T} . \tag{6.2}$$

L is determined by finding a pattern of black and white lines (a square-wave pattern) in which the lines are just wide enough for an observer to distinguish when they are presented through the TV system. L is the number of lines of that width that fit from top to bottom of the display. Observers may disagree somewhat as to when the pattern is no longer distinguishable, but this measure of resolution is widely accepted.

Johnson (1958) determined an empirical measure n for a certain class of targets under certain conditions. Alongside military targets at distances from a TV camera, he placed a number of square-wave patterns, differing with respect to the width of the lines. These patterns are defined in terms of the number of lines that fit across the minimum dimensions of the target (see Figure 132). When Johnson found that a particular target could be detected at a particular distance, he also found the bar pattern that could just be resolved at that distance. Therefore, visual performance can be described simply in terms of the number of just-distinguishable lines that fit across the minimum dimension of the target. This number is relatively independent of type of target and viewing distance. Table 42 presents his results.

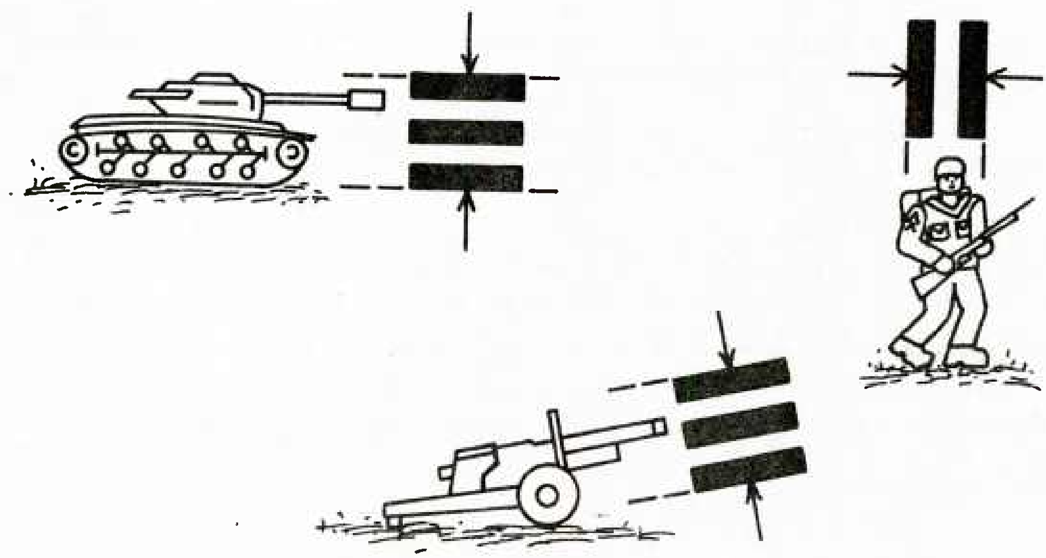


Figure 132. Method of optical image transformation (redrawn from Johnson, 1958).

Table 42

Resolution Values for Varying Targets

Target Broadside View	Resolution (in TV lines) per Minimum Dimension Detection	Orientation	Recognition	Identification
Truck	1.8	2.5	9.0	16.0
M-48 tank	1.5	2.4	7.0	14.0
Stalin tank	1.5	2.4	6.6	12.0
Centurion tank	1.5	2.4	7.0	12.0
Half-track	2.0	3.0	8.0	10.0
Jeep	2.4	3.0	9.0	11.0
Command car	2.4	3.0	8.6	11.0
Solder (standing)	3.0	3.6	7.6	16.0
105 howitzer	2.0	3.0	9.6	12.0
Average	2.0 ± 0.5	2.8 ± 0.7	8.0 ± 1.6	12.8 ± 3.0

It should be noted that, at long ranges, atmospheric conditions may greatly reduce contrast so that resolution is severely degraded. When this is the case, resolution in terms of number of TV lines covering the minimum target dimension will greatly differ from the actual or obtained resolution across the target. Also, Johnson used high contrast square-wave patterns to obtain resolution elements across the targets, which were military objects of low contrast. These facts do not invalidate Johnson's results, but the reader should be aware of them.

Figures 133 to 138 (adapted from Erickson, Hemingway, Craig, & Wagner, 1974) present the previous equations graphically for a variety of ranges (R) and show how maximum FOV or minimum L can be determined once the other parameters are known or assumed. For example, assume that a recognition range of 2 kilometers is needed against a submarine that is 3 m high in the water. If 15 TV lines are needed for identification, $T/n = .20$ (and $n/T = 5$). Figure 135 shows that, with a FOV of 2 degrees, a 350-line system is needed or that, with a 600-line system, the maximum permissible FOV would be 3.4 degrees.

Johnson's criterion can be used regardless of the resolution of the particular imaging system under consideration, since it is pegged to that resolution. Suppose the image of a submarine must be 8 mm high so that 14 TV lines can fit across it in a 500 line system. If the system resolution is cut to 250, Johnson's criterion would not change; the image would simply have to be made twice as large on the same display. Since resolution varies with target contrast and atmospheric conditions, it will usually be much poorer than indicated by close-range tests.

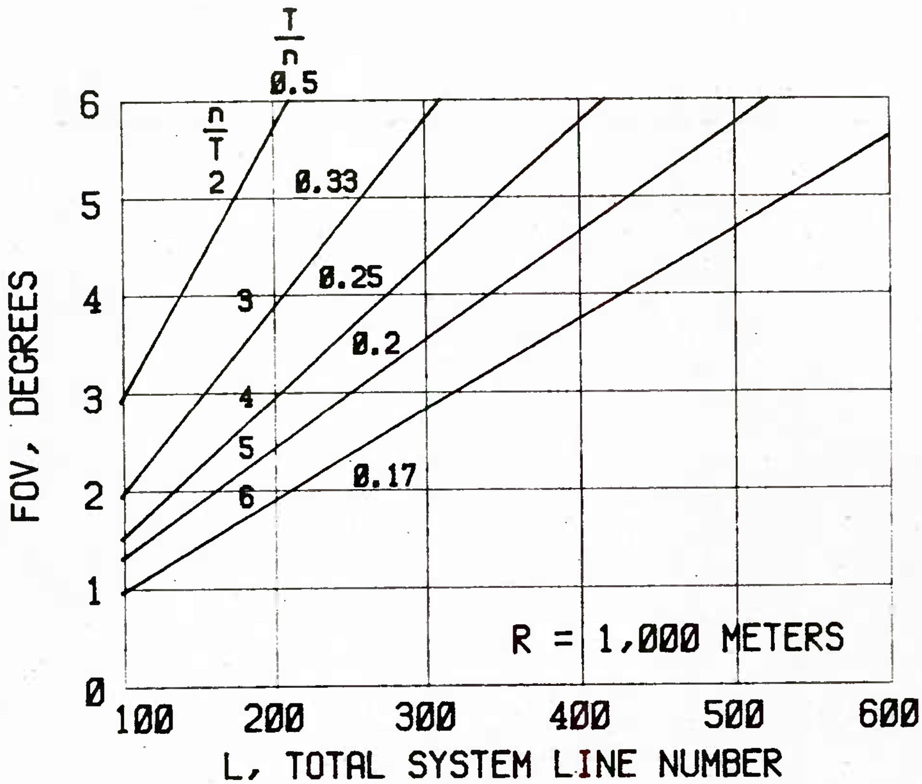


Figure 133. Graph of equations 6.1 and 6.2 for slant range (R) = 1 kilometer (taken from Erickson et al., 1974).

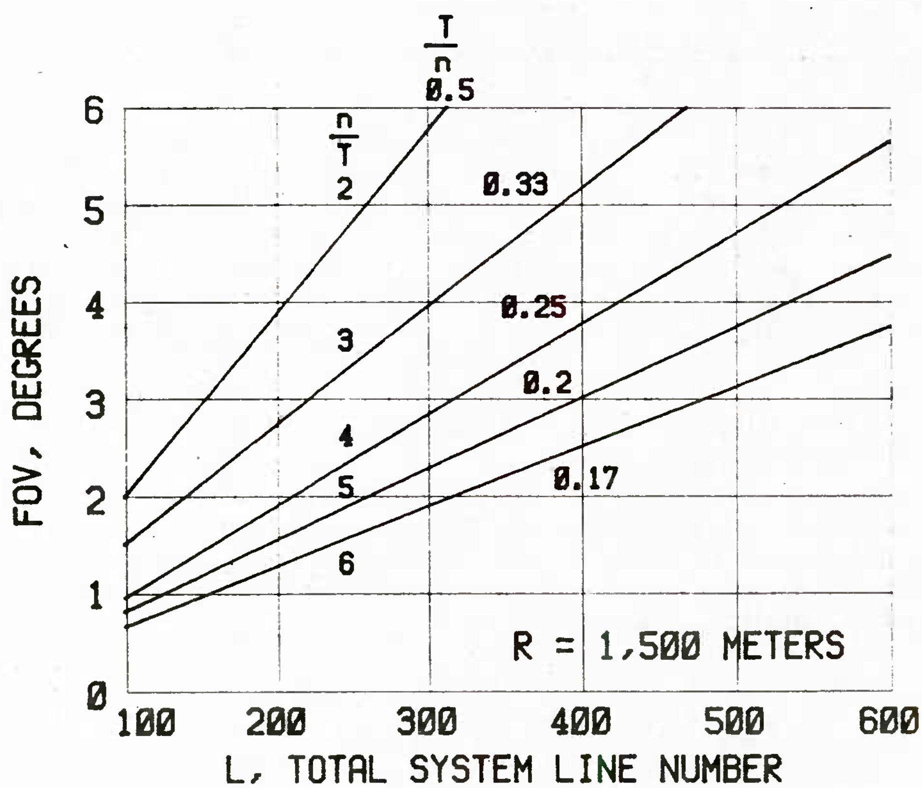


Figure 134. Graph of equations 6.1 and 6.2 for slant range (R) = 1.5 kilometers (taken from Erickson et al., 1974)

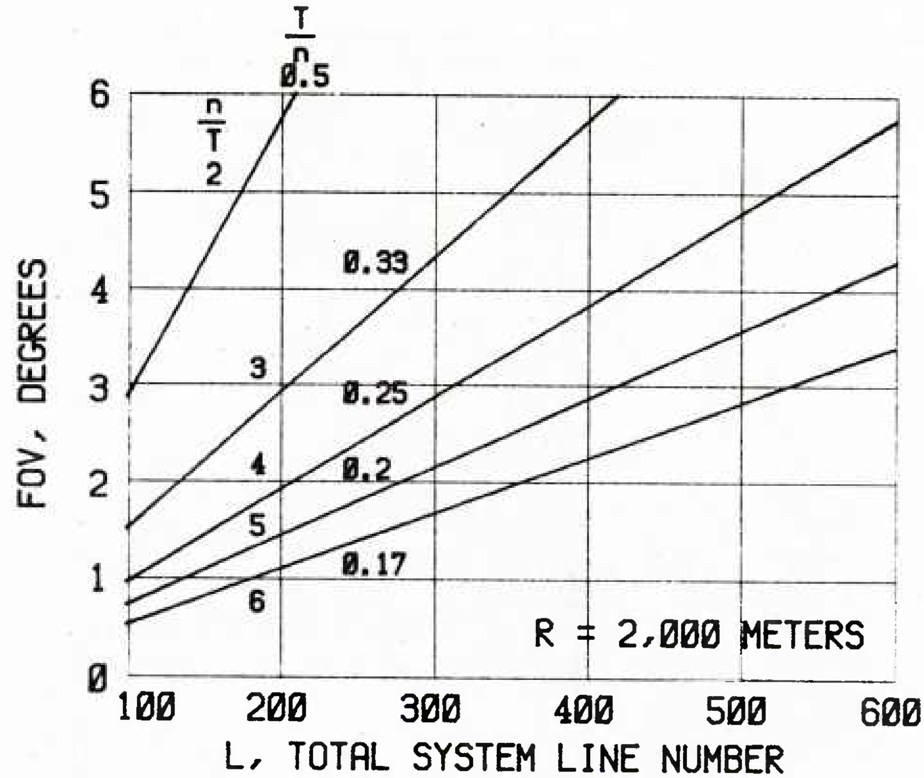


Figure 135. Graph of equations 6.1 and 6.2 for slant range (R) = 2 kilometers (taken from Erickson et al., 1974).

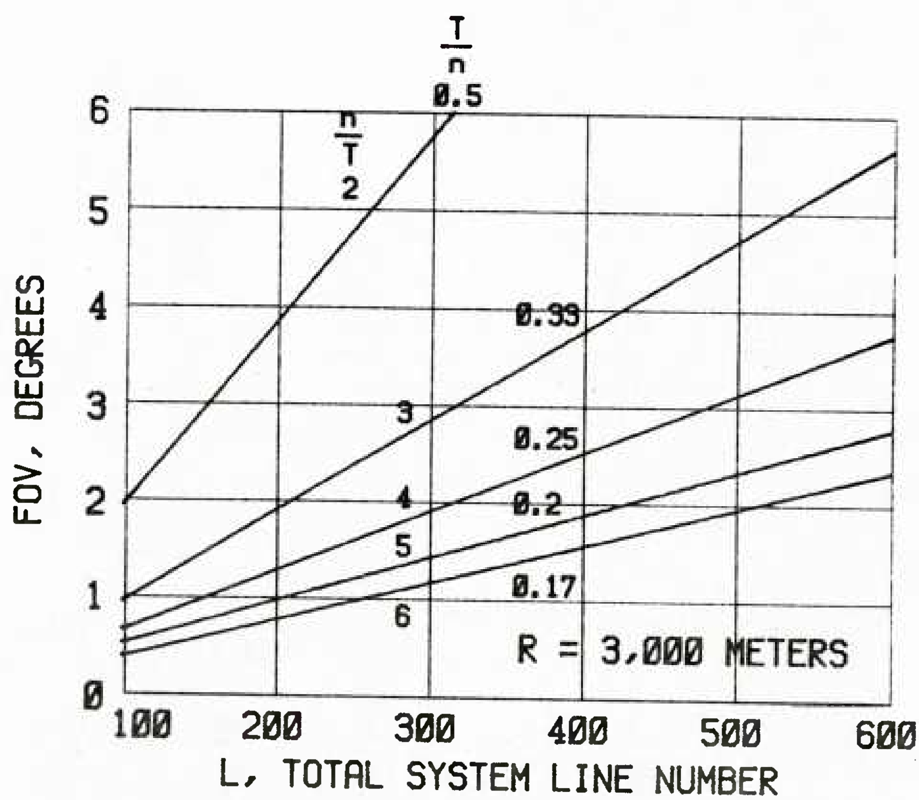


Figure 136. Graph of equations 6.1 and 6.2 for slant range (R) = 3 kilometers (taken from Erickson et al., 1974).

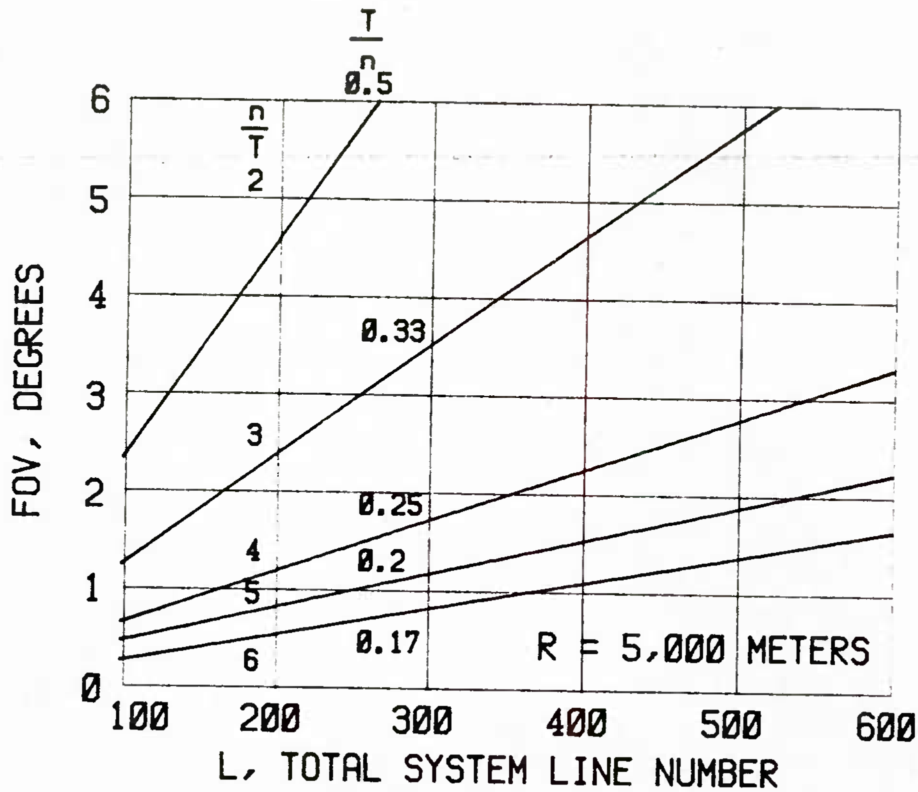


Figure 137. Graph of equations 6.1 and 6.2 for slant range (R) = 5 kilometers (taken from Erickson et al., 1974).

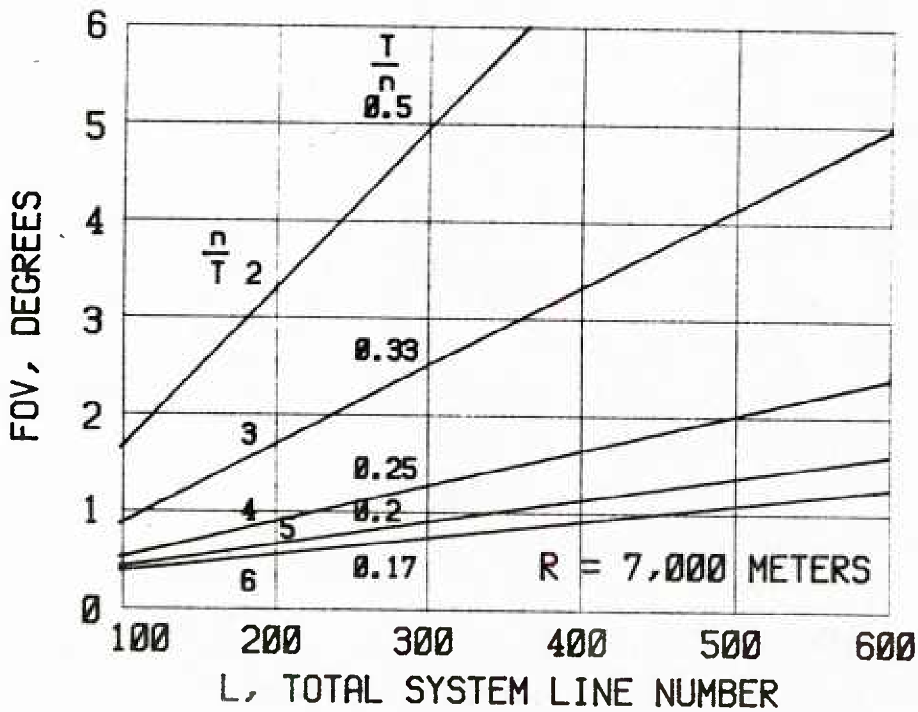


Figure 138. Graph of equations 6.1 and 6.2 for slant range (R) = 7 kilometers (taken from Erickson et al., 1974).

6.3 Number of TV Scan Lines

Others have tried to determine the required number of TV scan lines to be placed across the image. In applying this method, the resolution of the TV system employed in the studies must also be known because, when resolution changes, the required number of scan lines changes as well. Figures 139, 140, and 141 taken from Clarke (1975) show how target recognition time is reduced and probability of recognition improves as a function of the number of TV lines per picture height.

Figure 140 shows the results in an arbitrary score of performance in reading generated symbols, identifying aircraft, and identifying vehicles on TV displays. The optimum number of lines over image height is 28.

The number of lines per millimeter of image height is shown in Figure 141. The performance scores show that there is a flattening of each of the three curves at 3 lines per mm.

Erickson (1978) studied observer performance in counting number of targets present (zero, one, two, or three) as a function of TV scan lines making up the image. Subjects were required to search a square area subtending 6 degrees on a side on the monitor and state the number of targets in the square. Target contrast was approximately +18 percent (brighter than background) and -7 percent (darker than background).

All 18 percent contrast targets were seen when they were made up of three scan lines or more. Target images made up of 1.8 scan lines or less were not seen (performance was not better than chance) (Figure 142).

The experiment with lower contrast targets darker than their background (-7%) did not use target sizes large enough to obtain 100 percent correct performance. Figure 143 shows that target images of up to 2.9 scan lines were not visible. The transition to visibility occurred between three and four-plus scan lines. A 100 percent correct performance level might occur at an estimated six scan lines of image size.

Similar effects were noted for identification while viewing on a TV monitor a vehicle on a terrain-type background. Angular subtense of the image and the background against which the target was seen affected identification performance. Ten scan lines were sufficient for identification; increasing scan lines beyond 10 did not improve performance significantly. Note that a larger number of scan lines is required for identification than for simple detection of targets (See Figure 144) (Erickson, 1978).

Subjects were given 12 seconds to search a scene for a vehicle. The vehicle was located on a 90 m x 100 m terrain background that contained fields, trees, roads and hedgerows. The trees and bushes were about the same size and contrast as the vehicles. The vehicles were seen broadside from a look-down angle about 50 degrees below a horizontal plane. Four different vehicles were presented, but the subjects were required to indicate vehicle location only; no identification response was required since the subjects knew there would be a vehicle in each scene; their response was based upon the decision that an object was not a tree or bush.

The target images were made up of 7.0 to 26.2 scan lines. Analysis of the data shows that there was no increase in the ability to locate the vehicles as scan lines were increased; an image made up of seven scan lines was sufficient (Erickson, 1978).

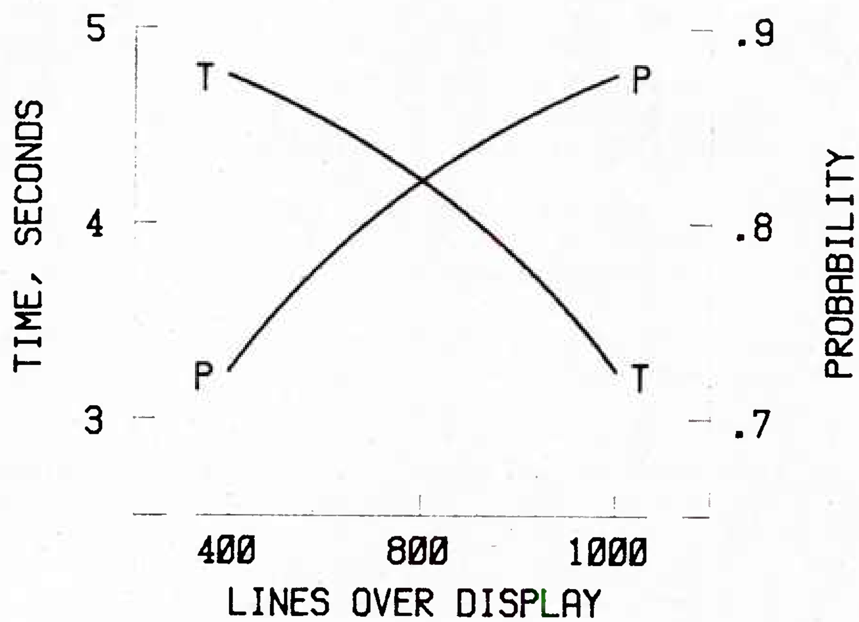


Figure 139. Variation in target recognition times and probability of recognizing target with number of lines per picture height.

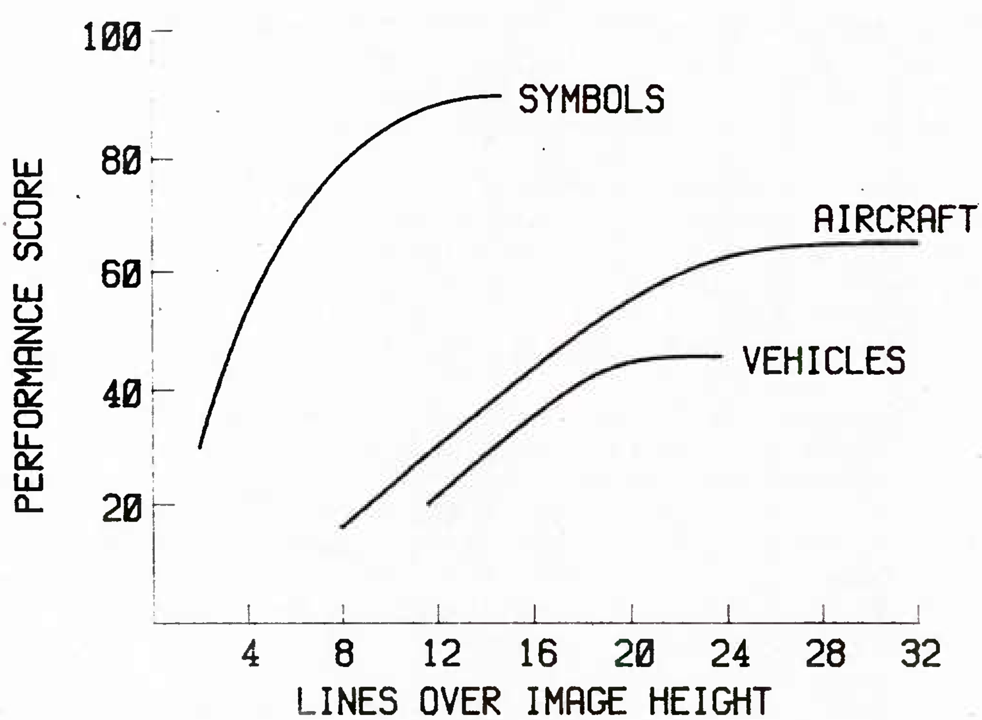


Figure 140. Performance score variation with lines over image height in three different tasks.

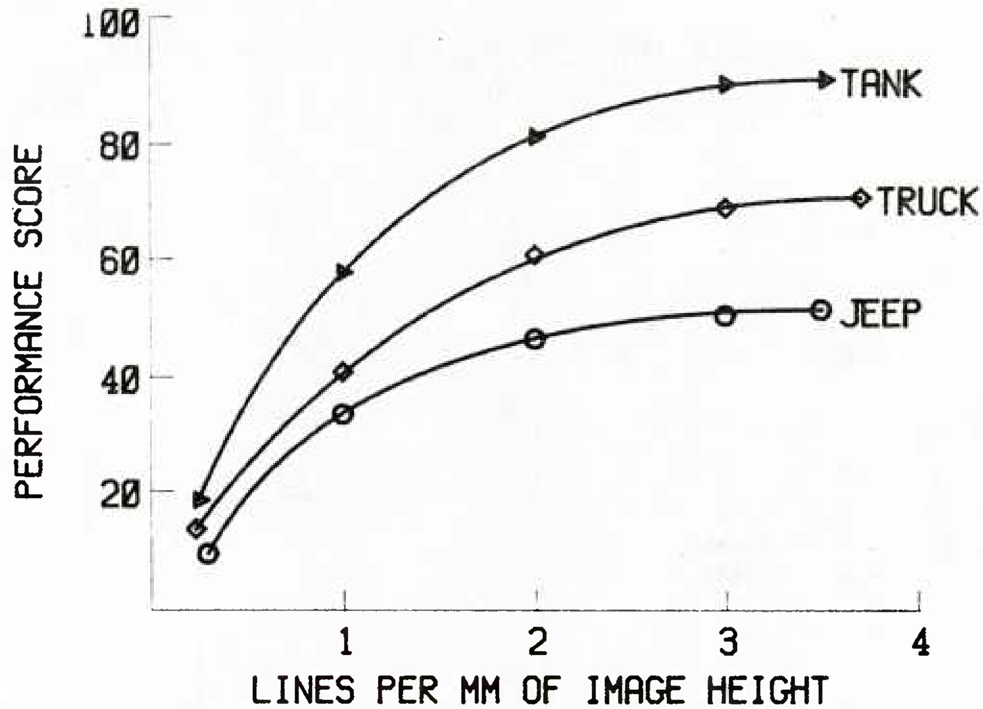


Figure 141. Discrimination performance.

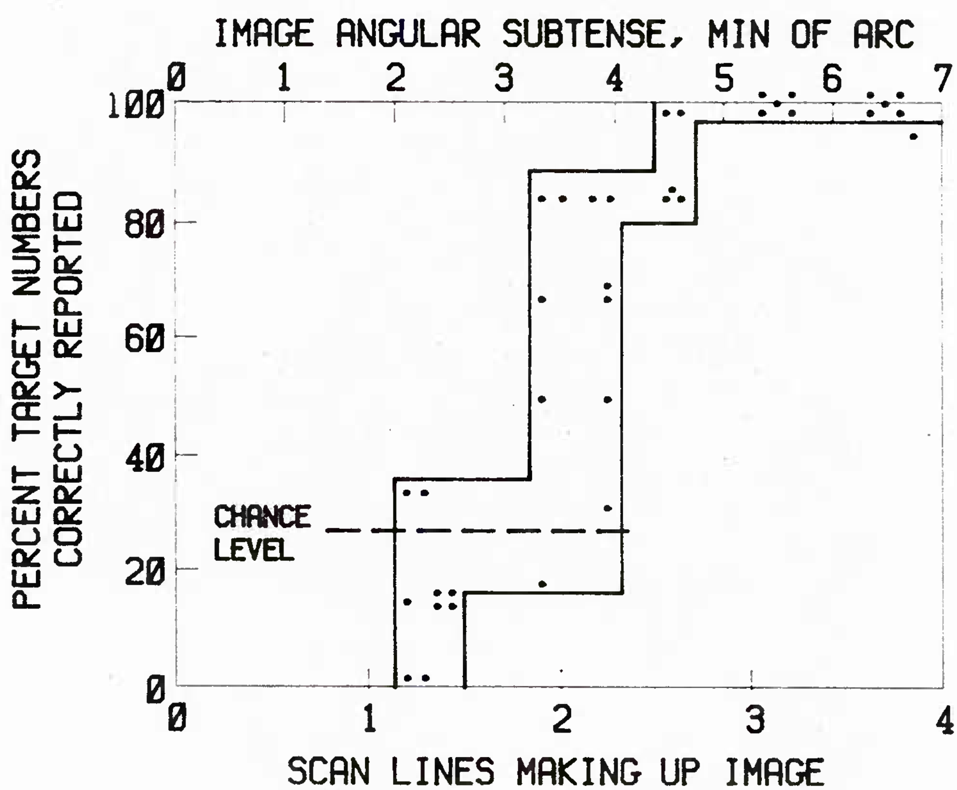


Figure 142. Observer performance in correctly counting number of targets present for 18 percent contrast targets. Each dot represents the percent correct responses by each S.

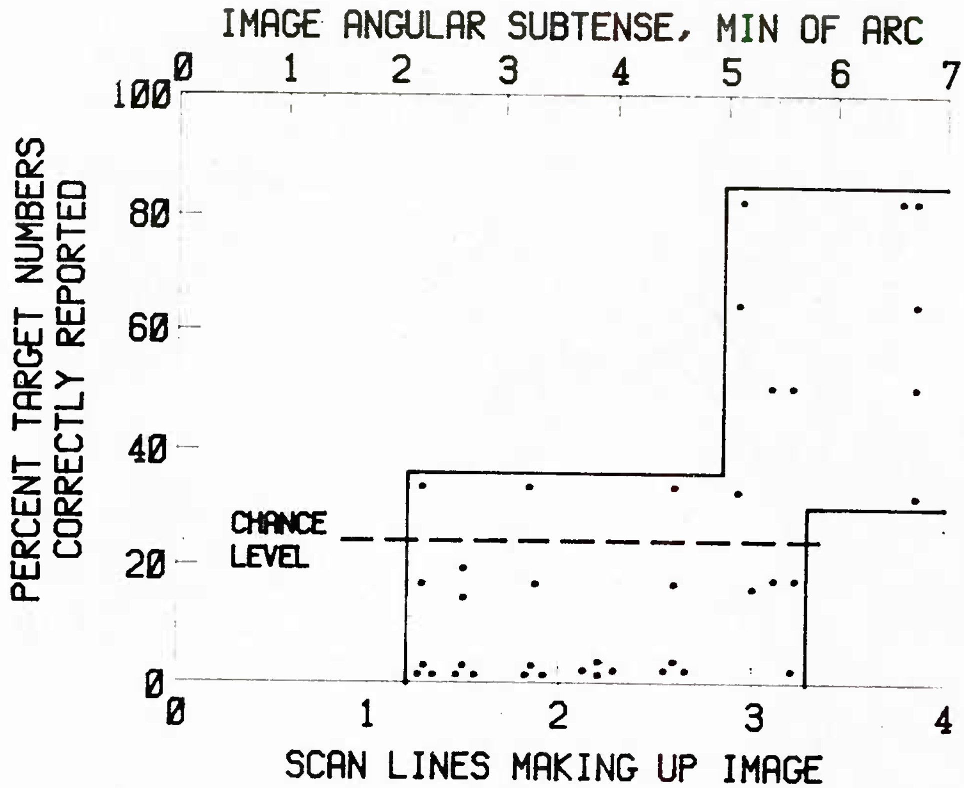


Figure 143. Observer performance in correctly counting number of targets present for -7 percent contrast targets. Each dot represents the percent correct responses by each S.

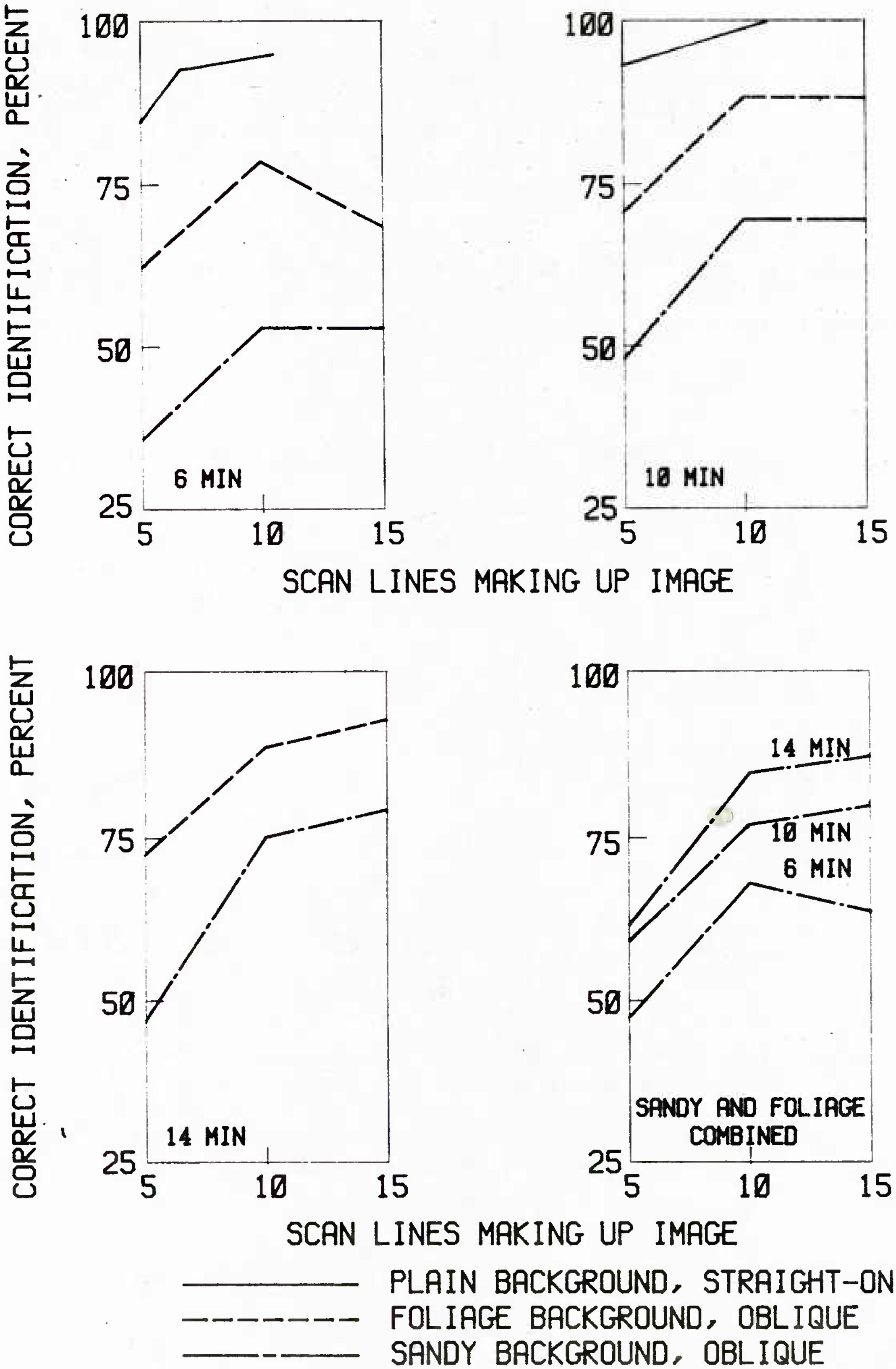


Figure 144. Vehicle identification on television. Target size, in minutes of arc, is given for each set of curves.

Part of a series of studies carried out at the Naval Weapons Center was a laboratory experiment to determine the range at which a ship could be recognized as a merchant ship or a combatant ship on television (Whitehurst, 1976). Video tapes were made of scale model ships under a variety of conditions and shown to six subjects. The effects of light azimuth, light elevation, ship orientation, and ship-wake size on the range at which subjects recognized the target were determined.

Light azimuth was the only one of the four independent variables that did not have a statistically significant effect on recognition range. Some of the data are shown in Figure 145. A high level of performance was reached under most conditions when the ship's image was made up of from 9 to 12 scan lines.

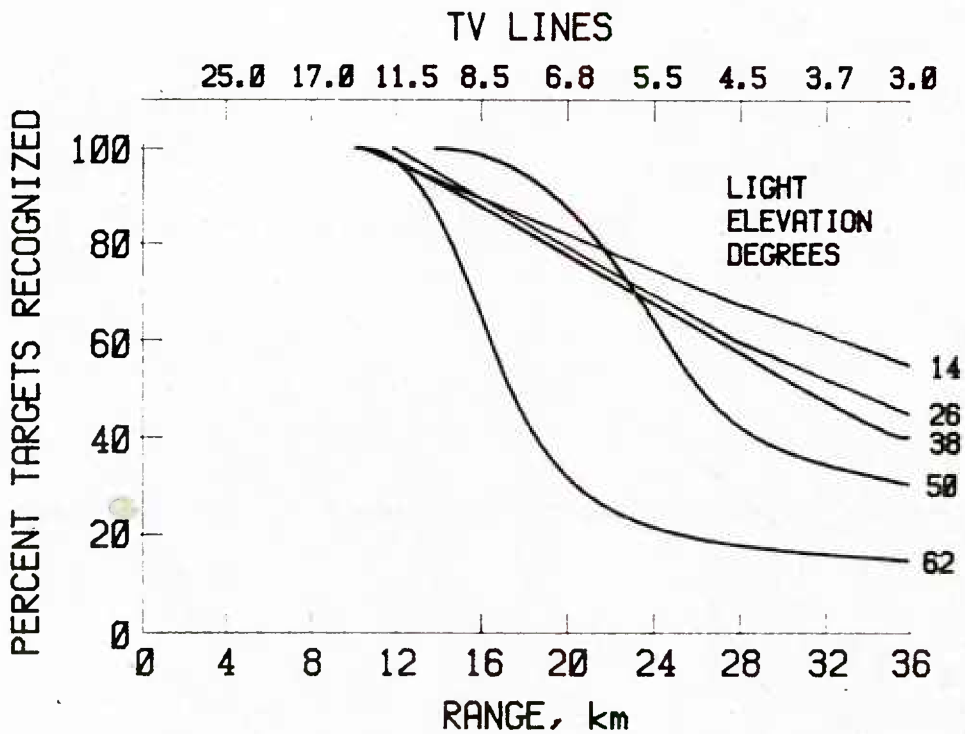


Figure 145a. Probability of ship recognition as a function of range and light elevation.

Figure 145. Probability of ship recognition as a function of range, light elevation, and ship orientation.

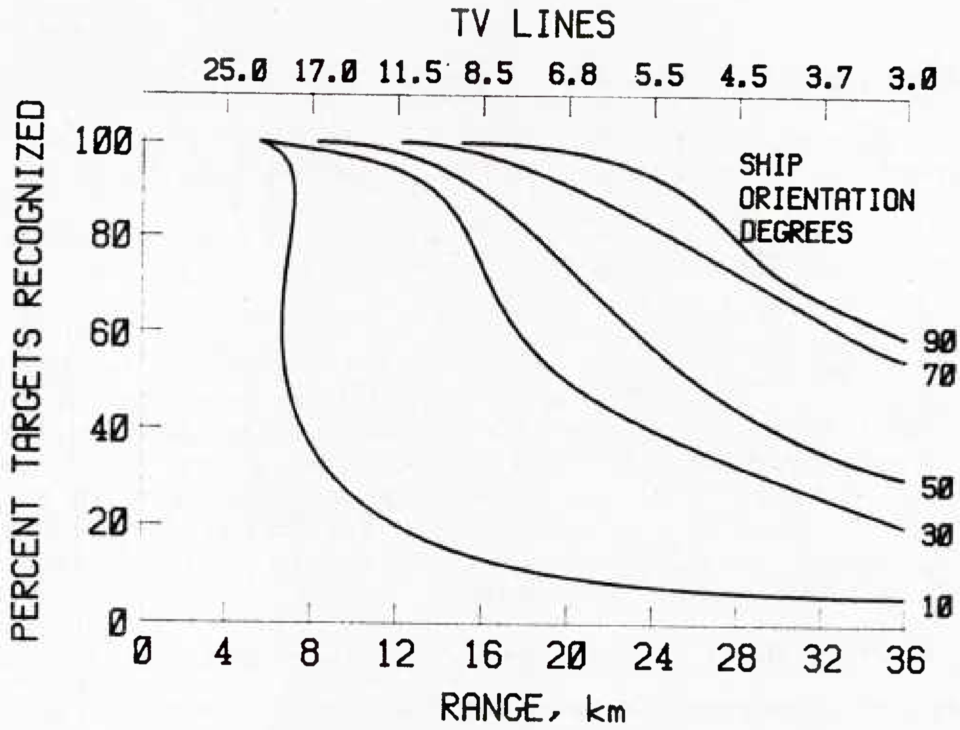


Figure 145b. Probability of ship recognition as a function of range and ship orientation. A broadside orientation is 90 degrees; stern-on is zero degrees.

6.4 Resolution

6.4.1 Measures of Resolution

Additional sources of information for electro-optical systems are Carel (1965) and Semple et al. (1971).

a. Shrinking raster resolution (see Slocum, Hoffman, & Heard, 1967). The technique involves presenting a raster of equally-spaced lines on a display and "shrinking" the spacing between these lines until the average observer can just barely perceive that lines are present. This normally occurs in the laboratory environment when there is about a 2 to 5 percent drop in luminance between adjacent lines. Assuming that the energy distribution in a CRT spot is normally distributed, the line spacing when this flat-field condition obtains is approximately 2 σ, where σ is the standard deviation of the point spread function or the radius of the spot at the point where its intensity is 60.65 percent of its maximum value.

b. Television resolution or TV limiting response. A square-wave bar pattern is displayed, and the spatial frequency (number of bars per linear dimension) of the pattern is increased until the observer can just detect the pattern. The limiting resolution is expressed as the number of black and white bars discernible per unit length (such as lines per picture height, or line pairs per millimeter.) One square-wave cycle (i.e., one black and one white line) is referred to as 2 TV lines. If a gaussian spot is again assumed, the limiting response is reached when the TV lines are separated by a distance of 1.18 σ. The number of TV limiting lines per unit distance exceeds the number of shrinking raster lines by approximately a factor of 1.7.

c. TV_{50} resolution. TV_{50} resolution is based on objective measurement is expressed as the separation between two points of light at which the intensity of the dark region between them is 50 percent of the intensity of their brightest points.

d. The 50 percent amplitude resolution. The 50 percent amplitude resolution (also known as the raster line width) is the width of a resolution element when its amplitude is 50 percent of its maximum level.

e. Modulation transfer function (MTF). MTF describes the response of a system to a sine-wave (rather than square-wave) target; the response is expressed as the ratio of output to input modulation as a function of spatial frequency. MTF is not as simple as other techniques for specifying resolution, because it is not expressed as a single number. The MTF curve is different for every point on the display and is "better" at the display center. It is useful, however, because, if the MTFs of all system components are known (e.g., lens of the TV camera, video amplified, CRT), the total system MTF is found by multiplying the MTFs of the components.

f. Equivalent passband (N_e). N_e is related to MTF in the following way: while MTF expresses the response of a system in one dimension, N_e is related to this response in two dimensions and thus is based on the square of the MTF (Snyder, Keesee, Beamon, & Aschenbach, 1973). The formula is:

$$N_e = \int_0^{\infty} (r)^2 \, dN, \tag{6.3}$$

where

r is the proportional sine-wave response, or modulation transfer factor and

N is the spatial frequency in TV lines/picture height.

N_e is the cutoff frequency for a rectangular response (perfect filter) function (one which drops abruptly from 100 to 0 percent), when the area of that rectangular response is equivalent to the area under the MTF^2 curve. The N_e measure provides a single score that is based on the response of the system across its total operating spectrum, rather than at any particular spatial frequency.

Several of the common resolution measures can be related to each other quite readily (Table 43).

6.4.2 Findings of Selected Studies of Resolution

a. Identification of (1) simple geometric forms on homogeneous backgrounds requires 4 to 9 TV lines; (2) scale models of military vehicles, 6 to 9 TV lines (Williams & Borda, 1964).

b. When horizontal TV resolution was varied from 300 to 800 TV lines, detection probabilities were significantly lower for 300 lines; no difference from 400 to 800 lines (Oatman, 1965a).

Table 43

Conversion Table for Several Measures of Display System Resolution where σ Equals the Standard Deviation (From Slocum et al., 1967)

From		To: TV Limiting	10% MTF	TV 50	Shrinking Raster	50% Amplitude	50% MTF	Optical	Equivalent Passband (N_e)
TV limiting	1.18 σ		.80	.71	.59	.50	.44	.42	.33
10% MTF	1.47 σ	1.25		.88	.74	.62	.55	.52	.42
TV_{50} (3 dB)	1.67 σ	1.4	1.14		.84	.71	.63	.59	.47
Shrinking raster	2.00 σ	1.7	1.36	1.2		.85	.75	.71	.56
50% amplitude	2.35 σ	2.0	1.6	1.4	1.17		.88	.83	.66
50% MTF	2.67 σ	2.26	1.8	1.6	1.33	1.14		.94	.75
Optical ($^1/_e$)	2.83 σ	2.4	1.9	1.7	1.4	1.2	1.06		.80
Equivalent passband (N_e)	3.54 σ	3.0	2.4	2.1	1.77	1.5	1.33	1.25	

c. With two conditions: (1) limiting horizontal resolution of 800 TV lines with 800 scan lines and (2) limiting resolution of 450 TV lines with 450 scan lines, detection scores were significantly better with higher resolution (Oatman, 1965b).

d. For small targets, TV detection range increases up to 600 TV lines; detection range for large targets is independent of resolution (Smith, S. L., 1962).

e. Increased resolution increases target detection/recognition performance but beyond a certain point increased resolution does not improve performance (Self, 1969).

f. Identification requires more resolution than does detection (Self, 1969).

g. Display resolution should be twice that of the effective resolution of the sensor (Slocum et al., 1967).

6.5 Display Size/Viewing Distance

Display size measured in terms of angular dimensions has relatively little effect on target acquisition performance. A number of studies indicate that, although there was a slight drop in performance as display visual angle decreased, the effects were not significant (Parkes, 1972; Bruns, Wherry, & Bittner,1970; & Bruns, Bittner, & Stevenson,1972).

Display angular size should not be so large that raster scan lines are easily visible. The resolution of the eye is accepted as 1 minute of arc and operators prefer to sit where raster scan lines subtend 1 minute of arc. Figure 146 presents the maximum permissable display height as a function of the number of active scan lines for a variety of viewing distances. The assumption is made that a scan line subtense of 1 minute is the point at which the lines begin to interfere with perception.

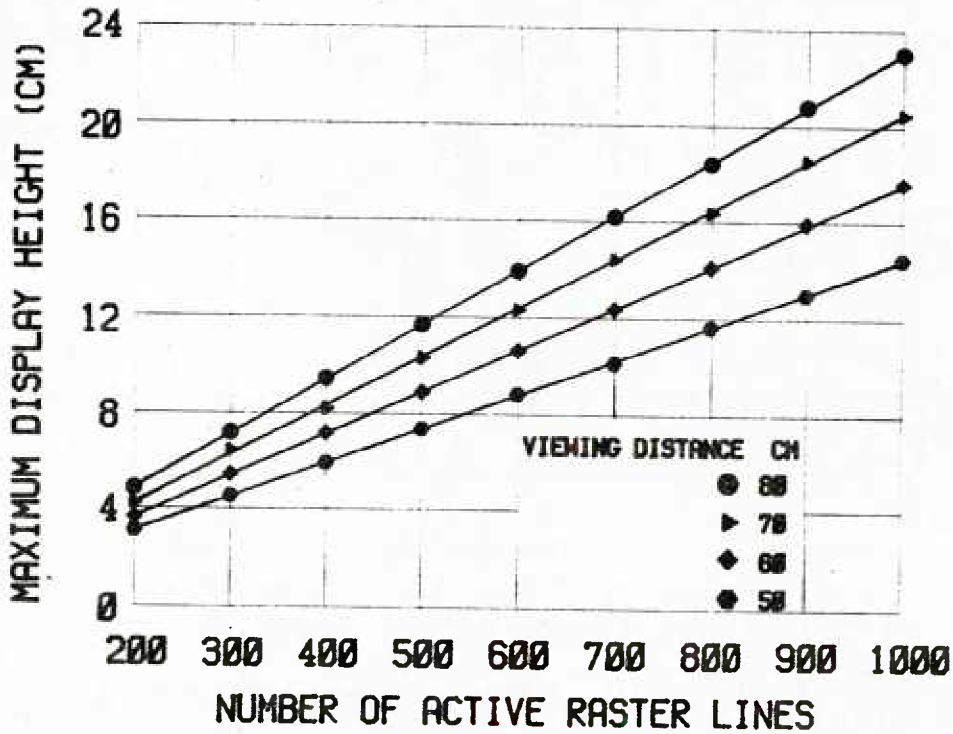


Figure 146. Maximum display height as a function of raster line density for several viewing distances. Raster lines are assumed to subtend no more than 1 minute of arc at the eye.

Display size is related to target size. Search speed and accuracy of target recognition are relatively poor when the target size is less than approximately 12 to 20 minutes of arc (Jones et al., 1974). This finding is valid across a range of resolution values. In determining display angular size, calculations should be made of the displayed sizes of various targets when seen by the sensor at representative slant ranges. If displayed angular sizes are below 12 to 20 minutes, increase display size or decrease the sensor FOV.

Search efficiency drops when display angular size is less than 9 degrees (Enoch, 1960) because a large percentage of the observer's eye fixations fall outside the display area. At display angles greater than 9 degrees, efficiency also decreases because observers tend to concentrate their fixations in the display center. Therefore, 9 degrees is recommended as the optimal display angle for highest search efficiency.

Variations in display size have no meaningful impact upon probability of target detection for pips on noise-free display presentations. However, the addition of symbology, information, or noise over and above target information has a marked impact upon probability of target detection for displays larger than only .75 inch in diameter. Figure 147 shows the interaction of display noise and size (Semple et al., 1971).

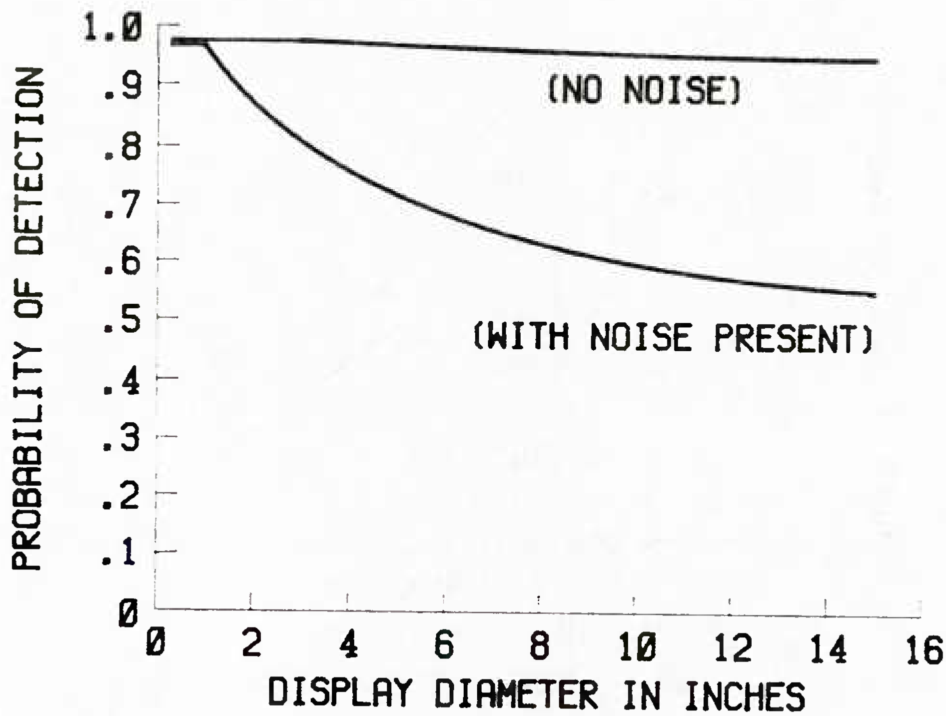


Figure 147. Probability of target detection on a PPI display as a function of display size and noise (taken from Semple et al., 1971).

A somewhat different approach to the problem of display size is to vary sensor field of view in conjunction with display size. The approach has particular application for considerations relating to the display of high resolution radar imagery.

Fundamentally, sensor field of view and display size can be related to human target detection performance through imagery scale factor and display size. For example, if display size is decreased while sensor field of view is held constant, the result is a reduction in scale factor of the displayed information because the same amount of information must be presented in a smaller area, requiring a reduction in scale factor (the relationship between inches of display dedicated to displaying inches of real-world content).

Simon (1965) performed a study of target recognition using simulated aerial reconnaissance radar imagery in which the simulated sensor field of view was held constant while display size (6 and 12 inches) was varied. With the sensor fields of view studied, the corresponding display scale factors were 1:216,000, 1:108,000 and 1:54,000. Observers were allowed a viewing time of 10, 20, or 40 seconds and were asked to recognize targets such as airfields, tank farms, and a stadium.

Figure 148 shows that both display size and imagery scale factor are related to probability of target recognition for each of the three viewing times studied. All these variables have marked impacts upon target recognition performance.

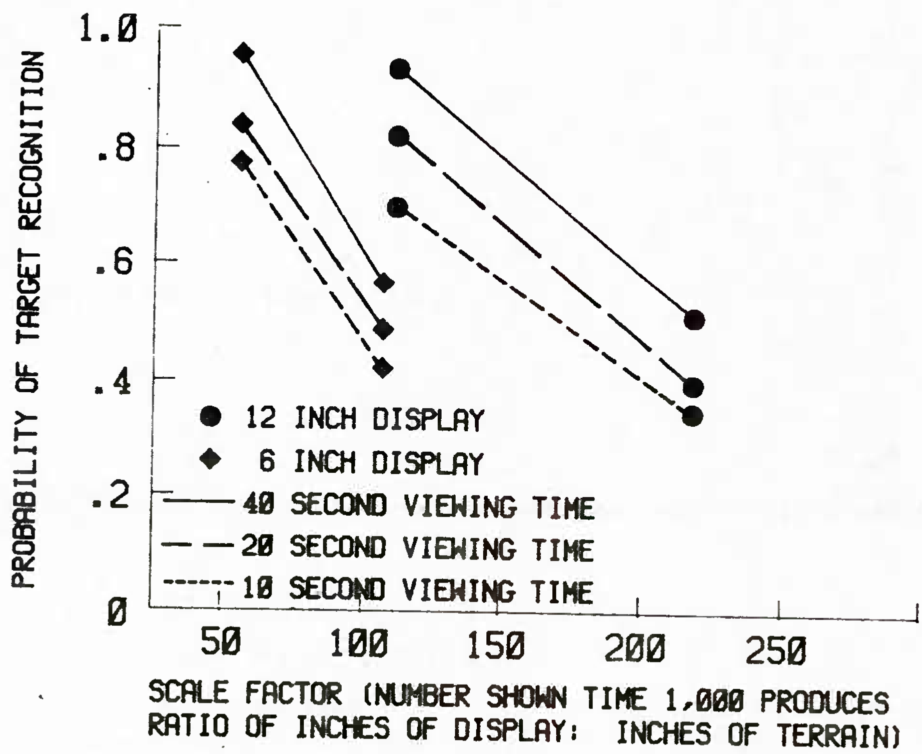


Figure 148. Probability of target identification from radar imagery as a function of display size and scale factor (taken from Semple et al., 1971).

It appears from Figure 148 that the effects of display size can be directly compared at the 1:108,000 scale factor. Performance with the 12-inch display was inferior to performance with the 6-inch display at this scale factor. Performance with the 12-inch display at the 1:108,000 scale factor was not much better than performance with the 6-inch display at the much higher scale factor of 1:216,000. When the 6-inch display curve is linearly extrapolated to the 1:54,000 scale factor, the 12-inch display should produce performance comparable with the 6-inch display. Therefore, the effects of display size upon probability of target detection seem to be fundamentally similar whether PPI or imagery presentations are involved. Smaller displays result in higher probabilities of target detection.

6.6 Display Luminance and Ambient Illumination

If dark adaptation is not a problem, relatively high display luminance levels are advisable. Laboratory experiments have shown that, as brightness increases, smaller objects and objects of lower contrast can be detected with the same level of confidence (Jones et al., 1974). The legibility of letters displayed on TV increases as display brightness increases from 1 to 40 fL with the greatest increase between 1 and 20 fL (Shurtleff, 1967). Parkes (1972) reported that target detection ranges increased as display luminance increased from .19 to 4.15 fL.

If stray light or glare falls onto the display face, visual performance can be degraded seriously. Ambient illumination on the display reduces the display contrast ratio. Use of filters in front of the display will increase display contrast ratio but may introduce other problems. For example, overall display luminance may be reduced. See Bruns (1971), Bruns and Miller (1969), and Ketchel and Jenney (1968) for a discussion of available filters. High contrast CRTs that combine filters with special phosphors have also been developed; these can be used even under conditions of direct sunlight. See Knowles and Wulfeck (1972) for an experimental evaluation of these CRTs.

Display luminance should be sufficiently high so that the luminance of the surroundings is at least 10 percent less than that of the display. A display contrast ratio of 8:1 would then be sufficient to discriminate seven shades of grey for an image of 8 minutes of arc (Slocum et al., 1967). If surround luminance is higher than that of the display by an order of magnitude or more, a much greater display contrast ratio (e.g., 30:1) is required for the same discrimination level.

If a surround brighter than the displayed scene background is unavoidable and if some estimate of these levels can be made, the following formula will estimate the increase in required target/background contrast over that required when surround luminance is equal to background luminance (Ireland, 1967):

$$C'' = C_{ref}\ (.95 + .05\ \frac{LS}{LB}), \tag{6.4}$$

where

C'' = Conservative estimate of threshold contrast for a given ratio, $LS/LB > 1$,

C_{ref} = Threshold contrast when $LS/LB = 1$,

LS = Luminance of the area surrounding the display,,

LB = Luminance of the background against which a target is seen.

If the value of C_{ref} is not known or assumed, it may be estimated from the following equation:

$$\log C_{ref} = -.368 - .253(\log LB), \tag{6.5}$$

where all terms are defined in equation 6.4. Equation 6.5 applies to the calculation of the target/background contrast needed for a .50 probability of discrimination, when the target

is brighter than its background and subtends 2 minutes of arc at the eye. Ireland et al. (1967) state that it is valid for values of LB from 0.1 to 200 mL (.318 to 636.6 cd per m^2), and that extrapolation beyond this value will underestimate C_{ref}.

To make these equations of greater practical value, two correction factors are recommended. First, to obtain the contrast required for .99 probability of discrimination, Ireland et al. (1967) calculate that equation 6.4 should be multiplied by a factor of 4.2. Second, to extend the results from a laboratory setting to a more realistic environment, a minimum multiplication factor of 6.25 is suggested.

Figure 149 presents the estimated contrast thresholds required for .99 probability of detection in a practical visual task involving no critical details smaller than 2 minutes of arc. These thresholds are presented as a function of background luminance (LB), for values of LS/LB ranging from 1 to 100.

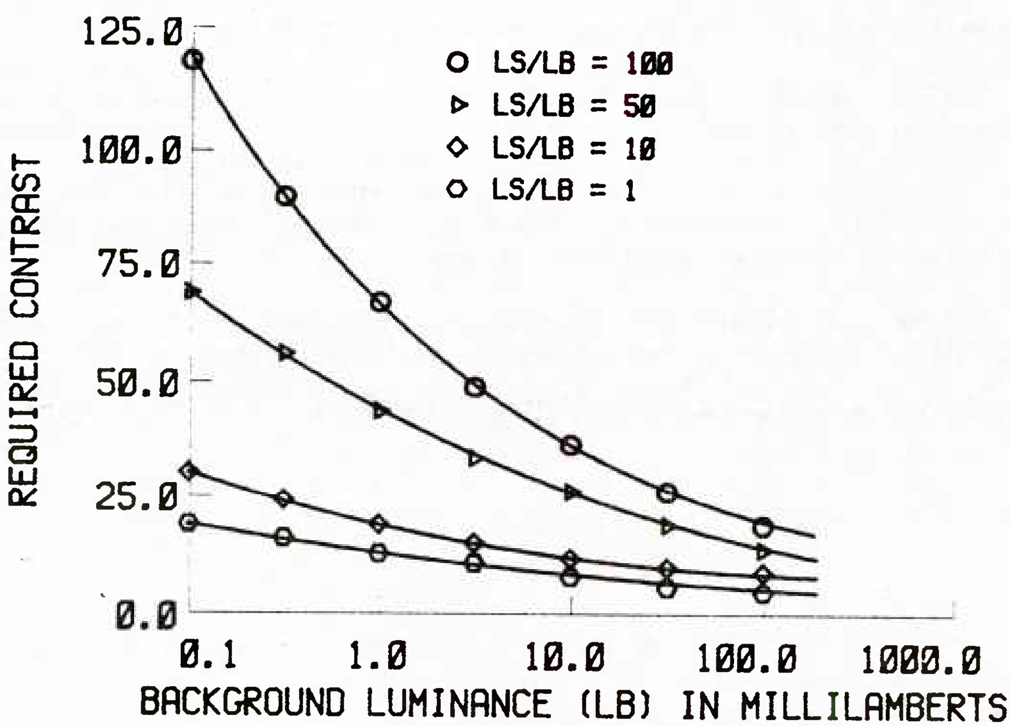


Figure 149. Estimated contrast required for detection probability of .99 in a practical visual task involving no critical details smaller than 2 minutes of arc. Presented for various ratios of surround luminance (LS) to background luminance (LB) (from Jones et al., 1974).

With regard to maximum display luminances for airborne visual displays, Ketchel and Jenney (1968) believe that 500 fL (1590 cd per m^2) should be sufficient for ordinary head-down display applications.

6.7 Display Contrast Ratio, Gamma, and Shades of Grey

6.7.1 Definitions

The gamma of a system is the slope of the function relating log input luminance to log output luminance. It can be considered as the contrast transfer function, since it determines whether the display contrast ratio is greater than, equal to, or less than the input contrast ratio.

Display contrast ratio is not the same as target/background contrast as defined previously. Display contrast is defined as the ratio of the brightest to the darkest portion of the displayed scene.

Shades of grey are essentially the same as gamma.

6.7.2 Performance Conclusions

Humes and Bauerschmidt (1968) found that the percentage of targets correctly recognized was greatest at a medium display contrast ratio (60) in comparison to ratios of 1.25 and 600. Another study (Russian) cited in Hairfield (1970) found that a contrast of 30 is good; a contrast of 100 is excellent and, above 100, display contrast ratio is of no value in improving image quality.

Fowler, Freitag, Jones, and King (1971) found that higher gamma generally resulted in better detection and recognition. Blackwell, Ohmart, and Brainard (1961) found in a target detection task while viewing vertical aerial photographs of a terrain model that target detection probability increased substantially as gamma increased. It is probably best to stay with gamma of about 1.0 (Jones et al., 1974).

The weight of the experimental evidence concerning the number of shades of grey that should be provided by the system is that from 7 to 10 shades is sufficient (Hairfield,1970; Slocum et al., 1967; Johnson, 1968; & Gaven, Tavitian, & Harabedian, 1970). The latter found that recognition times were 50% longer with 5 shades of grey as compared with 7 or 9 (at long ranges only). Greening and Wyman (1968, 1969) found that target acquisition performance in a test using radar imagery was positively related to the shades of grey. As grey increased from 3 to 5 to 11 shades, recognition probabilities increased from .56 to .67 to .82 and latency decreased from 11.0 to 8.6 seconds. The effect is shown graphically in Figure 150 taken from Clarke (1975).

The scores have been put on a scale of 100 to indicate the percentage change in target recognition times brought about by using differing numbers of shades of grey.

Erickson (1978) presents similar data (Figure 151).

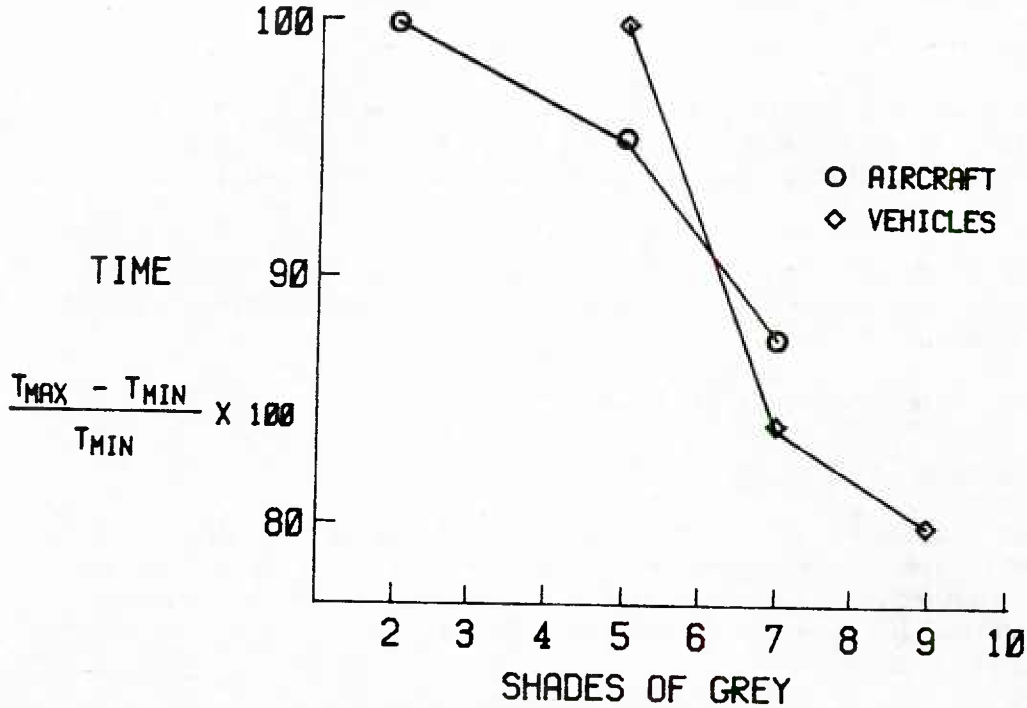


Figure 150. Changes in target recognition times as a function of number of shades of grey.

Figure 151. Percent and number of correct responses for scan lines and grey shades.

6.8 Signal-to-Noise Ratio

6.8.1 Definition

Perceptual performance becomes degraded as the signal-to-noise ratio (SNR) of a system decreases. Performance improves as a function of SNR up to some point (approximately 16 to 25 dB), beyond which further increases in SNR are of little or no importance.

Signal-to-noise ratio is commonly defined as the ratio of the peak-to-peak signal amplitude to the root-mean-square (rms) noise. Peak-to-peak signal amplitude refers to the difference between the maximum and the minimum signal values; rms noise can be considered as the standard deviation of the random fluctuations around a given signal level. Signal-to-noise ratio is often expressed in units of decibels (dB), rather than as a simple quotient; that is,

$$\text{SNR (in dB)} = 20 \log_{10} (\text{peak-to-peak signal} / \text{rms noise}). \tag{6.6}$$

6.8.2 Sample Study Results

Parkes (1972) had subjects locate targets in oblique terrain photographs and varied noise level for SNRs of 30, 24, 19, and 14 dB. There was no significant performance decrement with 30 and 24 dB; there was significant improvement between 24 and 19 dB. Williams et al. (1965) found no performance differences among SNRs of 15, 20, and over 50 dB. Humes and Bauerschmidt (1968) studied SNRs of 1, 7, 16, and 37.6 dB; the 16 dB condition was the level below which performance deteriorated. Hillman (1966) maintains that detection or recognition of small targets is degraded more by high, spatial-frequency noise than by low frequency noise. Noise is most detrimental when its frequency matches that of the objects being searched for.

General conclusion: Target acquisiton performance is a negatively accelerated increasing function of SNR. The particular value of SNR, beyond which little further benefit is obtained, depends on idiosyncratic factors. Hairfield (1970) concludes this critical SNR level lies between 16 and 25 dB.

Clarke (1975) indicates that target detection is possible with low ratios but the identification performance requires higher SNRs (Figure 152). The falling performance in detection is attributed to the increase in false alarms as the task became easier.

Figure 153 shows how minimum perceptible acuity increases as the bandwidth of the information increases. There is little difference between 18 and 36 dB, but an increase of 12 dB from 6 to 18 dB makes a big difference.

Figure 154 shows how observer's subjective assessment of picture quality varies with bandwidth and SNR. These data are from tests done with digital television. At 3 dB, an increase of 15 dB will shift subjective picture quality from barely marginal to fair. The quality is not good for any SNR at .5 dB. In digital television, a low SNR appears as "snow" and a low bandwidth (the sampling frequency) causes the image to blur. Similar results are reported by Erickson (1978) as shown in Figure 155.

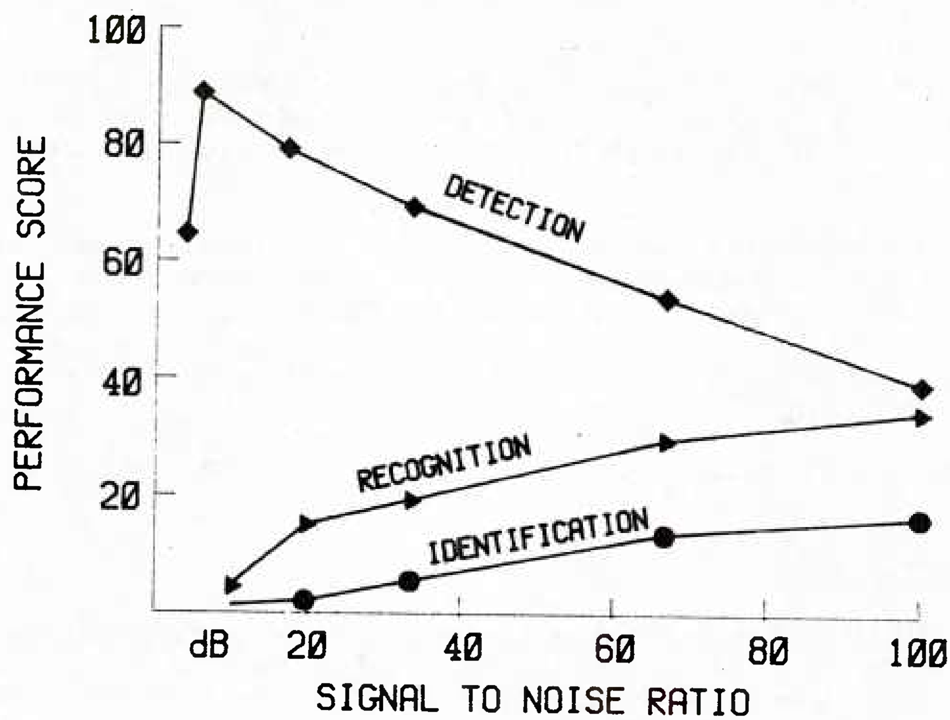


Figure 152. Performance in a discrimination task with variation in picture SNR.

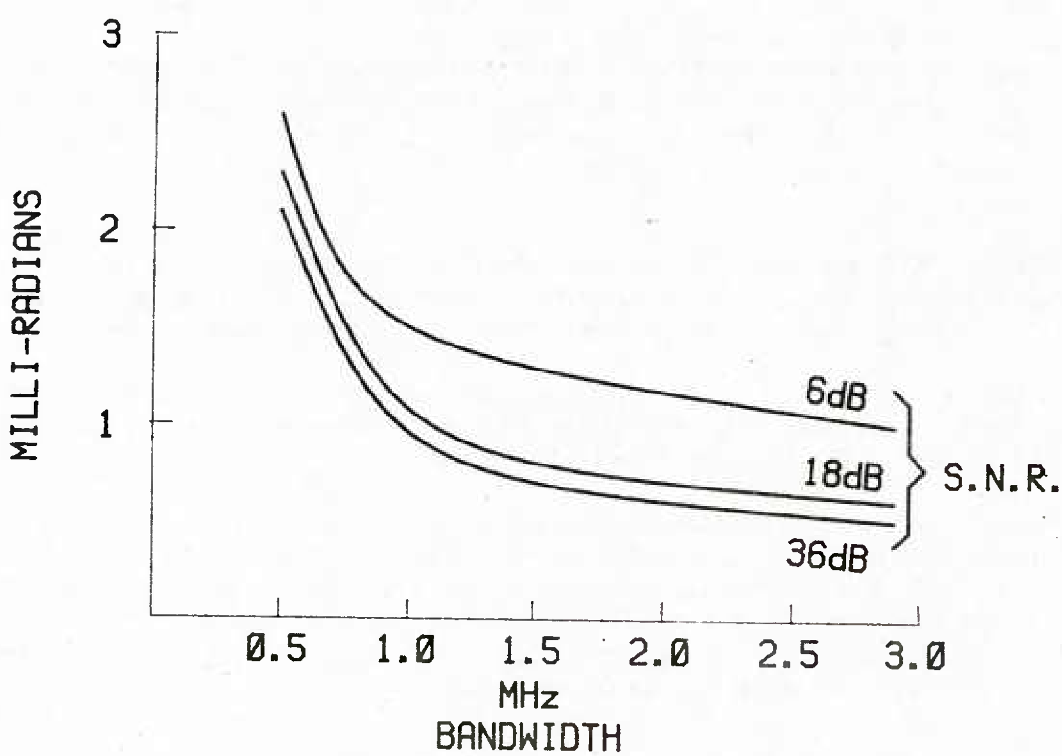


Figure 153. Minimum perceptible acuity as a function of bandwidth.

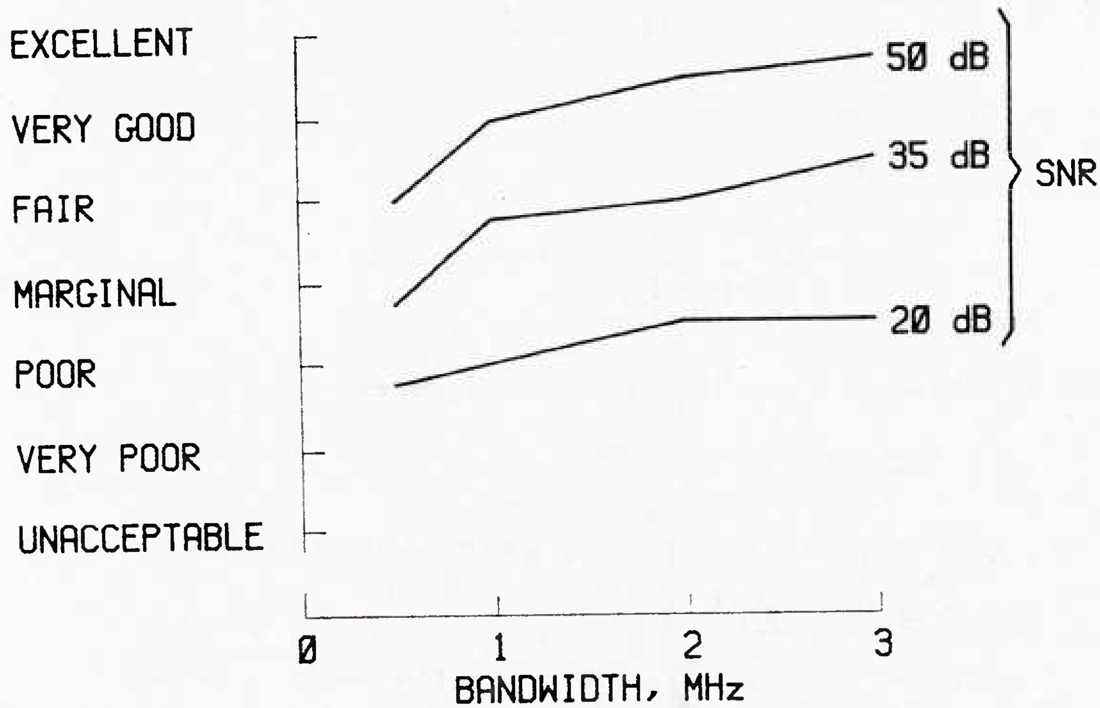


Figure 154. Subjective assessment of picture quality as a function of bandwidth and SNR.

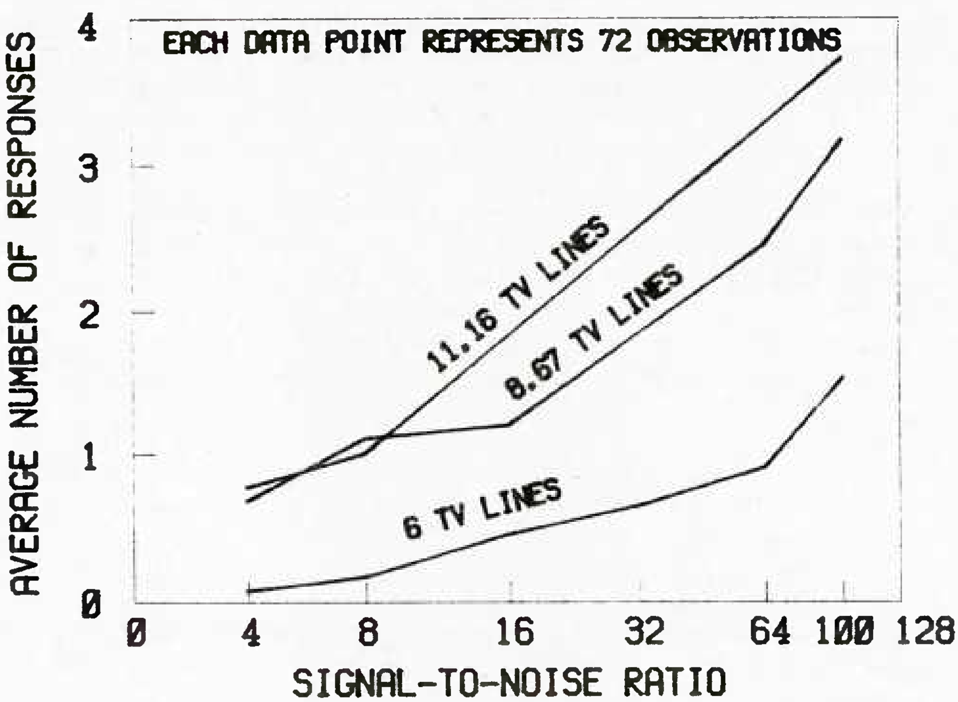


Figure 155. Correct target classification responses as a function of SNR.

The number of scan lines (l) making up a target image on the display can be determined by the following equation:

$$l = \frac{2N \arctan \frac{h}{2R}}{(FOV)} \tag{6.8}$$

where

h = projected target height,
N = total actual line number of the system,
R = range to the target, and
FOV = field of view of the sensor.

Equation 6.8 can be approximated for small target subtenses by:

$$l = \frac{57.29\, hN}{R(FOV)}, \tag{6.9}$$

where FOV is given in degrees. Equation 6.9 is accurate enough for most applications.

6.9 Color vs. Black and White

Because black and white TV systems convert a scene into an image that varies only in luminance level, some potentially useful information may be lost. Some authorities have suggested that acquisition performance might be improved substantially if this extra information were available to the observer, particularly when operating at low altitudes and in clear weather.

Only a few realistic studies have been designed to investigate the use of color TV systems in target acquisition. These studies have generally failed to demonstrate clear-cut differences in detection performance as a function of color contrast. Christ and Teichner (1973) concluded that color can be an effective aid to performance under some conditions and it can be detrimental in others. If the observer has been briefed concerning the colors of certain classes of targets, his performance might improve.

Fowler and Jones (1972) investigated whether the use of a color television display would enhance detection or recognition performance. They found no advantage due to the color display, regardless of whether the target colors were similar to, or different from, their background colors. Later research in the same laboratory employed lower target/background brightness contrast values than had been used in the earlier study. The results again failed to demonstrate any advantage resulting from the use of color displays.

Snyder, Greening, and Calhoun (1964) and Parkes (1972) arrived at essentially the same conclusion. No significant differences were found in mean recognition ranges or percent correct recognitions.

It is doubtful whether presenting the observer with a realistic color picture of the scene is particularly advantageous in most air-to-ground operations. One reason for this is that the atmosphere reduces color contrast (cf. Middleton, 1952). Another is that most military targets lack much color contrast.

6.10 Image Frame Integration Time

One way to reduce image blur caused by high angular rates of motion is to decrease the length of time during which the sensor collects information before the information is transferred to the display. This may be done by increasing the frame rate, so that radiant energy is integrated over 1/60 second, for example, instead of 1/30 second. However, this solution is costly because bandwidth would have to be doubled for the resolution to remain the same. Another solution would be to maintain the same frame rate, but shutter the sensor so that energy is integrated over only a fraction of the frame interval. This procedure is feasible only if the scene radiance level is high enough so that the S/N ratio can remain at an acceptable level.

Humes and Bauerschmidt (1968), using a frame rate of 30 per second, studied integration times of 1/60, 1/150, and 1/300 second. With the camera pointing almost straight down, resulting in highest ground angular rates, target recognition probability was slightly, but significantly, higher at 1/150 or 1/300 than at 1/60 second. Recognition latency was faster for the 1/300 condition. With an oblique viewing mode, however, performance was generally unaffected. Similar increases in performance by reducing blur through shorter exposure times have been reported by Hoffman and Greening (1967).

6.11 Display Freeze

Target acquisition performance may be limited by the effects of target motion across the display. At relatively high velocity/height (V/H) ratios, coupled with a small field of view, a substantial proportion of targets may leave the display before the observer has had time to identify them or their angular rates may be too great for them to be identified accurately, especially with image smear. A logical solution is to freeze the image at some point, to permit the observer to make a more thorough search of the scene or a more detailed inspection of the target.

Freeze may be initiated by the observer or it may be automatic, based on nagivational information. It may be for a fixed duration, or until the operator terminates it. It may also be continuous consisting of a series of stopped frames of limited duration. Some of these parameters were investigated in two studies performed by Rusis, Snyder, and Greening (1965) and Rusis, Snyder, Greening, and Rawlings (1965). Subjects searched for and recognized tactical targets while watching a TV display of a dynamic scene.

The results show that display freeze can be very helpful. In the first experiment, recognition performance in the observer-initiated freeze mode improved in comparison to no freeze, at slant ranges beyond about .4 km. As the duration of the freeze increased from 1 to 5 seconds, performance worsened. An automatically-initiated display freeze, such as could be provided by a computer tied in to an accurate navigation system, was superior to an observer-initiated freeze. A continuous freeze condition (every 3 seconds) was inferior to other freeze modes. In the second study, observer-initiated freeze was again found superior to no freeze in terms of recognition probabilities; but average recognition and designation slant ranges were longer without freeze.

These experiments indicate that display freeze can in fact enhance recognition performance. Whether this advantage has enough practical significance to justify the additional cost is questionable. Although some image blur may be eliminated by this procedure, a considerable amount of blur is still present.

6.12 Sensor Pointing Angle

Some research has been performed to determine the depression angle at which a sensor should be fixed in order to maximize detection or recognition ranges. Carter (1962) utilizing FOVs from 10 to 26 degrees found the optimal depression angle for recognition to be 30 degrees at an altitude of 3000 ft (914 m) and 20 degrees at an altitude of 1500 ft (457 m). For a given FOV, the ground area being taken in by a camera decreases as altitude decreases. This effect can be compensated for by decreasing the camera depression angle, which results in an increase in ground coverage, thereby increasing the amount of time a target remains displayed.

Humes and Bauerschmidt (1968) studied camera pointing angle in conjunction with camera FOV and aircraft V/H ratio. The results are shown in Figure 156. At a low V/H value (.05), recognition performance was poorest at a depression angle of 26 degrees, better at 45 degrees, and still slightly better at 82 degrees. At higher V/H values, optimal performance was obtained at the 45 degrees pointing angle, and poorest performance again was found at 26 degrees. In line with Carter's (1962) results, the advantage of the more forward-looking angle (45 degrees) is greater at the lower altitude. Lower velocity resulted in substantially improved recognition performance regardless of viewing angle, although this effect was most pronounced for the "nadir" viewing mode (82 degrees).

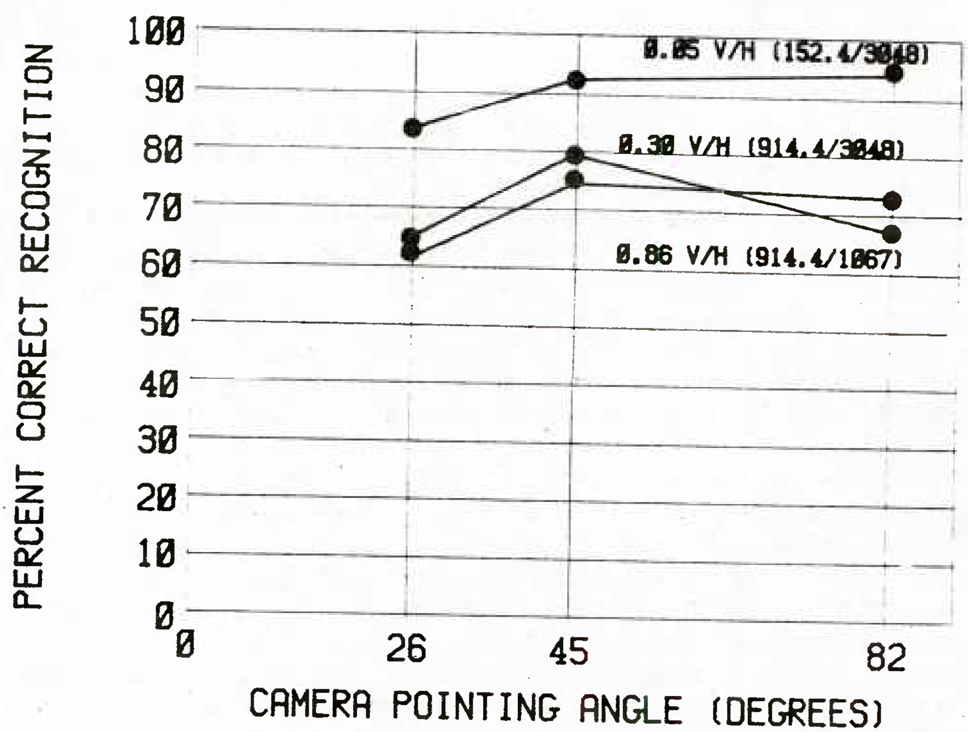


Figure 156. Percent correct recognition for oblique and nadir viewing modes: camera pointing angle by V/H interaction (V specified in meters per second; H in meters).

The sensor FOV should also be taken into account when determining optimal pointing angle. Humes and Bauerschmidt (1968) found recognition performance was best with a narrow FOV, but as the degression angle increased, larger FOVs were advantageous. Under shallow viewing angles, a vertical FOV of 18 or less degrees is advisable; for a pointing angle of 45 degrees, a vertical FOV of approximately 26 degrees, and for nadir viewing angles, a vertical FOV of approximately 47 degrees appears optimal.

6.13 Raster Orientation

It has been suggested that target acquisition performance with line-scanned images might be enhanced if the raster scan lines were oriented in a vertical direction, contrary to common practice. The reasoning behind this suggestion is that most targets seen from the air are elongated in appearance so that their width is much greater than their height. Display resolution is very often superior in a direction parallel to the raster scan lines. It, therefore, makes sense to orient the display so that maximum resolution is in the direction where it is most needed--namely, where the target spatial frequency is higher.

Rusis (1966) investigated the effects of raster orientation in a target recognition task and found that vertical scan line orientation was superior to horizontal orientation.

Bruns et al. (1972) investigated this variable with a TV system in which resolution was approximately equal in the two dimensions. Small performance differences were again found, in favor of the vertical scan line orientation. The only statistically significant difference was for detection slant ranges (11% greater slant range for vertical orientation); identification ranges and probabilities were not significantly different.

In systems where the difference between horizontal and vertical resolution is substantial, serious consideration should be given to orienting the display so that maximum resolution is in the vertical direction. On the other hand, if the resolution difference is small, it seems unlikely that very large performance differences will result from changes in raster line orientation.

6.14 Orientation of TV Scan Lines

Erickson and Hemingway (1970) reported an experiment on the effect of television line structure on image legibility. Observers viewed triangular forms, circular forms, and an oblique air-reconnaissance photograph of suburban-type terrain on a television monitor at different viewing distances. The monitor on which the scenes were viewed was rotated so that the scan lines were horizontal, vertical, and slanted 45 degrees to the right or left to the observers. The observers' task was to determine the orientation of the scan lines. Figure 157 shows that the observers' ability to perceive the scan lines is a function of scan line angular subtense (the greater the viewing distance the smaller the subtense of the scan lines in the experiment). The authors conclude that, under most viewing conditions, scan line structure will be visible on the type of TV system used in their study and that raster line structure should be considered one of the system parameters that affect TV viewing.

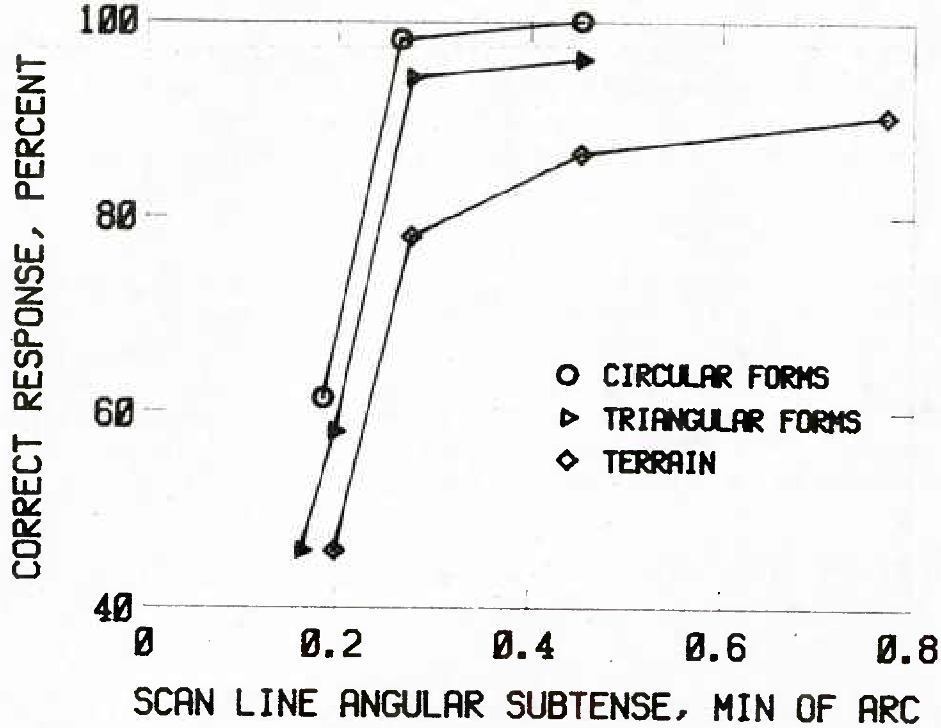


Figure 157. Mean performance on recognition of TV scan-line direction.

6.15 Raster Noise

Figure 158, in which three raster noise levels are plotted against target visual subtense at correct target recognition, indicates that a nearly perfect linear relationship between the angle subtended by the space between raster lines and the target subtense. Targets have to be 30 percent larger at the highest level of raster noise compared to the lowest level of raster noise tested.

Figure 159 shows the effect of raster noise on word readability. Again, a nearly perfect linear relationship between raster noise, as measured by the angle subtended by the space between raster lines, and operator performance was obtained. Words had to be 30 percent larger to be correctly read at the highest level of raster noise compared to the lowest level of raster noise. This 30 percent performance difference between the highest and lowest levels of raster noise was also obtained for a target recognition task experiment.

The display designer should be advised that failure to reduce spurious raster noise to acceptable levels will result in degradation of the operator's performance. At the raster frequency, 1.5 percent MTF is a safe acceptable design standard from the observer's point of view.

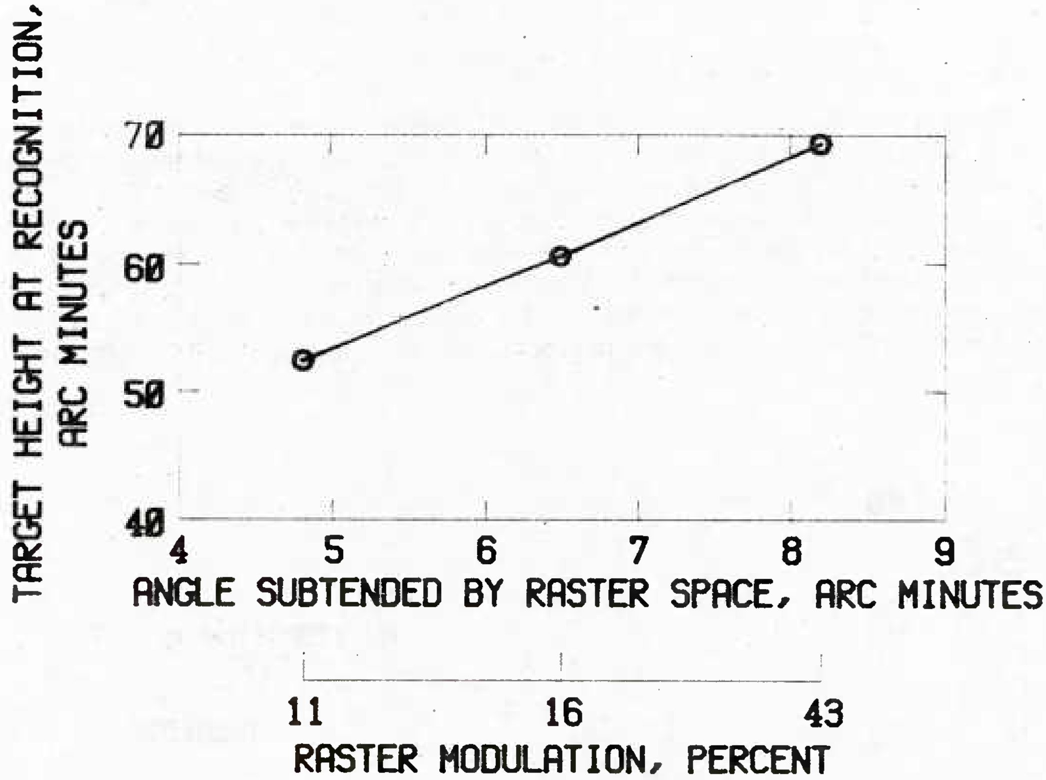


Figure 158. Effects of raster noise on target recognition performance.

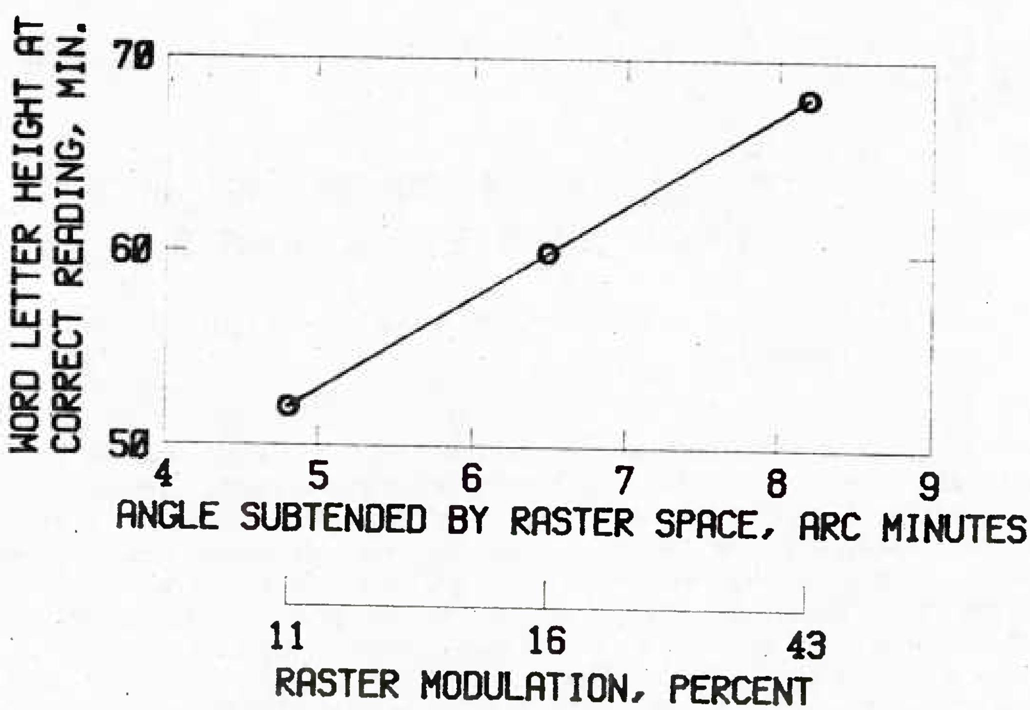


Figure 159. Effects of raster noise on word readability.

6.16 Effects of Vibration on Target Recognition

The effect of vibration on target subtense at recognition threshold is shown in Figure 160 (Hughes Aircraft Company, 1976). Targets were consistently recognized at a smaller size under the no vibration condition. At the point where 50 percent of the targets were recognized, target subtense under the no vibration condition was 13 arc minutes compared to 30 arc minutes for the vibration condition. The percent of targets correctly recognized was 75 percent under no vibration and 69 percent under vibration. Mean target subtense at recognition was 22.5 arc minutes under no vibration and 30.3 arc minutes under vibration--a 35 percent performance degradation due to vibration.

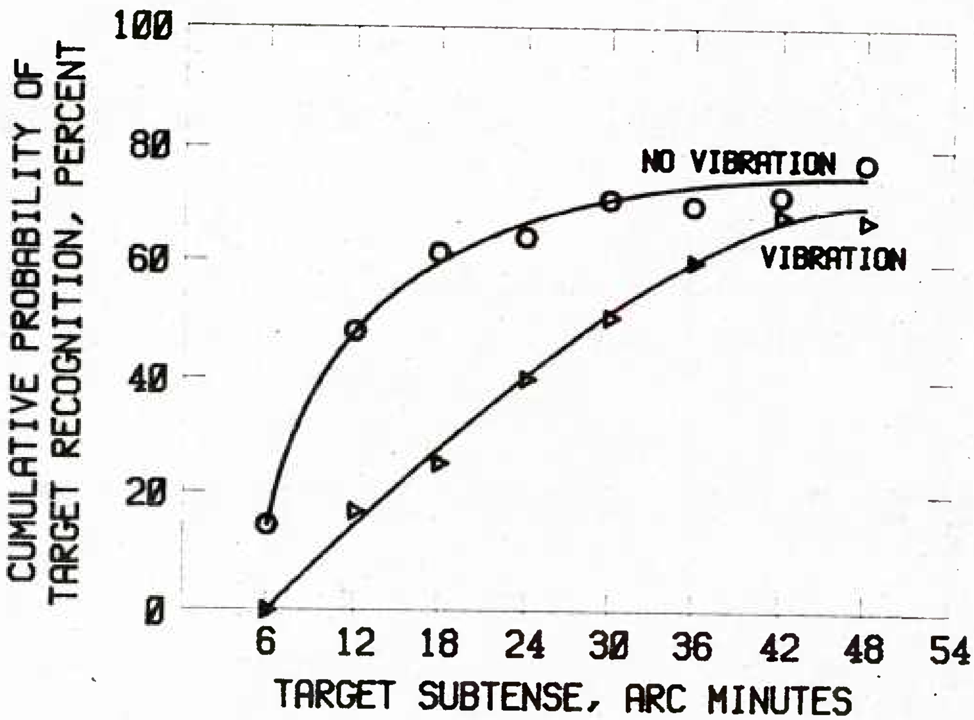


Figure 160. Effect of helicopter vibration on tactical target recognition.

The impact of the 35 percent increase in target subtense required for threshold recognition under vibration may be considered from three aspects: its implications for display size, sensor field-of-view, and range-to-target. For example, under vibration conditions for a desired target recognition and for a given sensor field of view, a 35 percent larger display is required to maintain performance levels equivalent to those obtained under static conditions. Conversely, equivalent performance can be maintained for a fixed size display by decreasing sensor field of view 26 percent and, similarly, for a given display size and sensor field-of-view, equivalent target recognition performance under vibration will result in a 26 percent shorter target recognition range compared to no vibration.

Hughes Aircraft Company (1976) found no significant interaction between the vibration and the key sensor system variable of resolution. Thus, it appears that 35 percent vibration field factor is valid for application to various electro-optical sensor system designs.

6.17 Image Enhancement

When an image is being created, many factors can degrade the quality of the finished product. Typically, contrast is reduced in comparison with the original scene and the transitions (edge gradients) between areas of different luminance are gradual rather than abrupt. A number of video processing methods (most importantly, edge sharpening by subtracting its second derivative from a video signal) have been devised in order to enhance the contrast between a target and its background. Brainard and Caum (1965) found that enhancement produced substantial improvements in several performance measures. Further, as the task difficulty increased, from simple detection to identification, the relative magnitude of the improvement increased.

Rusis (1966) also found that image enhancement by an edge sharpening technique can be beneficial. The number of correct recognitions increased and the number incorrect recognitions decreased, when image enhancement was present. The beneficial effect of enhancement was greater at short slant ranges and for heavily masked targets in comparison with moderately or lightly masked targets.

A study by Humes and Bauerschmidt (1968) showed that the amount of enhancement may determine whether performance is improved or degraded in a particular situation and that signal-to-noise ratio must be taken into account. A medium (1:1) level of enhancement produced faster recognition speeds than zero or high (3.5:1) enhancement. The same trend, although not statistically significant, was found for other performance measures. When S/N ratio was high, a high degree of image enhancement was beneficial; but at relatively low S/N levels, performance worsened as image enhancement increased. Edges worsened rather than improved so that images were degraded.

SECTION 7

MATRIX DISPLAYS

7.0 MATRIX DISPLAYS

7.1 Dot Mosaics

The coarsest mosaic capable of providing easily legible alphanumeric symbols is a 5 by 7 dot mosaic (see Figure 161). Only 35 decoded lines are required. If only numerics and a limited number of symbols are required, some elements are not required and the number of dots may be reduced to 27 as shown in Figure 162. Characters generated in 5 x 7 dot matrices are probably marginal in comparison to those generated in larger matrices. EG&G presents the following recommendations, which seem to bear out the previous material (Banks et al., 1982):

a. DIN--5 x 7 minimum dot matrix, one additional dot position (or 10% of character height) upward for upper-case ascenders, two dot positions (or 20% of character height) downward for lower-case descenders, with capital letter width 50 to 70 percent of the character height.

b. DCIEM--5 x 7 minimum.

c. VDT—5 x 7 minimum, 7 x 9 or greater preferred, with capital letter width of 70 to 80 percent of height.

7.2 Stroke Mosaics

The bars, strokes, or segments are arranged in a pattern similar to that shown in Figure 163. The segments may be electroluminescent strips, electrochemical cells, or cathodes in a glow discharge tube or they may be back or edge lit by neon or incadescent lamps. The characters are nearly as legible as those made from a 5 by 7 dot mosaic, but logic (switching) requirements are reduced from 35 inputs for the full 5 x 7 matrix to 16, 14, 9, or 7, depending on the font style chosen. The same height/width stroke ratios apply as for shaped characters. They have little effect on legibility except under degraded conditions. Stroke-width-to-height ratios ranging from 1:6 to 1:10 are recommended. Stephenson and Schiffler (1968) found 16 and 23 segment fonts to be more legible than 17, 27, or 38 segment fonts.

7.3 Display Variables

Some of the twelve variables likely to affect the observer of a symbolic matrix display are the same variables as in other electronic displays; others are peculiar to the matrix display.

a. Symbol definition. The number of emitters making up a symbol is termed symbol definition. For alphanumeric characters, the definition is often given in terms of the number of horizontal and vertical elements in the symbol matrix. Thus, a 5 x 7 symbol definition would be 5 horizontal elements by 7 vertical elements. As the number of elements defining the symbol increases, the fidelity of the symbol improves. Larger symbol matrices allow dot matrix symbols to more nearly approximate solid printed symbols.

b. Emitter size. Emitter size is defined by the physical extent of the active light emitting area. In those cases where the transition is gradual (see emitter edge luminance gradient), the 50 percent luminance point is taken as the edge of the emitter. For square emitters, size is described as the length of a side, while, for circular emitters, the diameter is used.

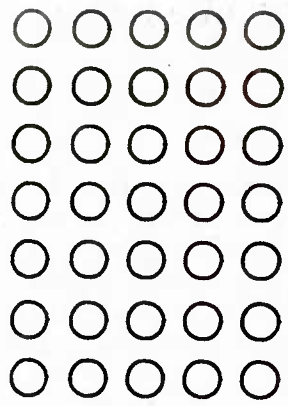


Figure 161. Full 5 x 7 dot mosaic (35 elements, full alphanumeric) (Luxenberg & Kuehn, 1968).

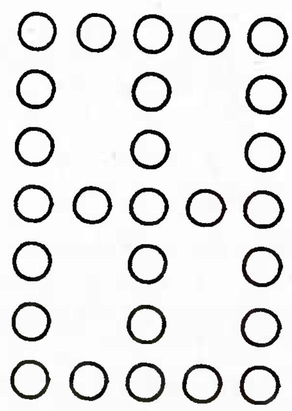


Figure 162. Reduced 5 x 7 dot mosaic (27 elements, numeric only).

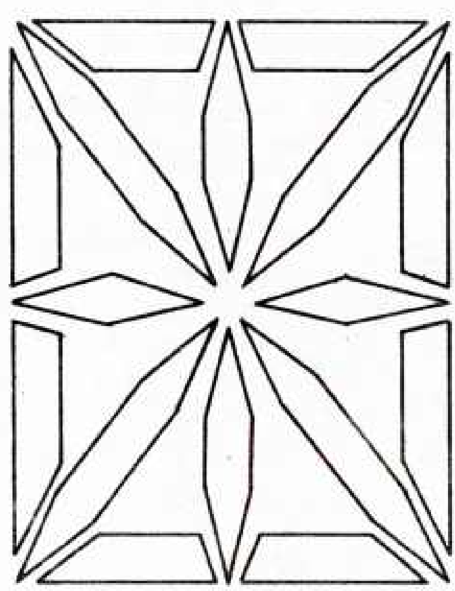


Figure 163. Stroke Mosaic (16 element).

If the viewing distance (d) is known, then the visual angle (θ) subtended by an emitter of size h can be calculated using the relation:

$$\theta \quad = \quad 2 \tan^{-1} (h/2d). \qquad (7.1)$$

For $\theta < 5$ degrees, θ in minutes of arc is accurately given by

$$\theta \quad = \quad 3438h/2 \qquad (7.2)$$

For a fixed viewing distance, changes in emitter size will result in changes in visual angle. However, if both emitter size and viewing distance are changed, it is possible that the visual angle may not change. The visual angle subtended by an individual emitter is a more behaviorally meaningful definition of emitter size.

Emitter size is similar to cathode ray tube (CRT) spot size with one important exception. With a conventional CRT, it is possible for adjacent spots to overlap one another. With a matrix display, each emitter is discrete and no overlap is possible.

c. Emitter spacing. The physical distance between the centers of adjacent emitters is the emitter spacing. As with emitter size, a more meaningful metric from the observer's point of view may be the angular subtense between emitters.

d. Percent active emitter area. In typical matrix displays, not all of the area occupied by a symbol is capable of emitting radiant energy. For square emitters, changes in emitter size produce equivalent changes in percent active area if the emitter spacing is held constant. The square of the ratio of emitter size to emitter spacing equals the active area. Because the emitter size can equal the spacing, the percentage of active area can range from 0 to 100 percent.

Different emitter shapes and matrix types yield different relationships for percent active area. A circular emitter with a diameter equal to the emitter spacing will yield only 78.54 percent of active area as opposed to the 100 percent achievable with the same emitter size and spacing but a square shape. Hexagonal emitters can achieve 100 percent active area only if they are arranged in a honeycomb type matrix. In an orthogonal matrix, the maximum active area is 75 percent.

e. Emitter shape. Conventional displays offer very little in the way of different emitter shapes, while matrix displays are potentially capable of almost any geometrical configuration emitter. Possible matrix emitter shapes include the circle, square, and hexagon.

f. Emitter packing format. With matrix displays, it is not necessary to retain the conventional orthogonal X,Y type of packing format. For hexagonal or diamond shaped emitters, an orthogonal matrix may not be appropriate. Nonorthogonal matrices will result in every other row of emitters being offset from the previous row as shown in Figure 164.

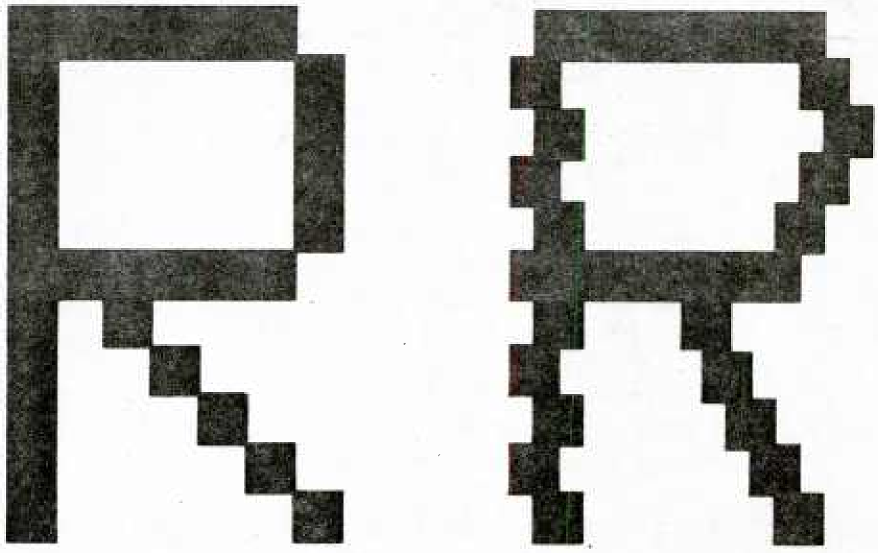


Figure 164. Example of the effect of varied emitter packing format on the alphanumeric character, R.

For square and circular emitters, the packing format will have no effect on the maximum active area as previously noted. However, for hexagonal, diamond, and other shapes of emitters, the choice of an appropriate nonorthogonal matrix will result in a higher packing density with a concomitant increase in the maximum active area.

g. Emitter edge luminance gradient. The distribution of luminance across a conventional CRT spot is approximately Gaussian, which results in a smooth transition from light to dark at the edge of the spot. Matrix displays have the extent of this transition as a variable. The transition may be very sudden and sharp or it may be gradual.

Emitter edge luminance gradient is included as a spatial variable, although it could be considered a luminance variable. It is defined as the slope of the transition from 90 to 10 percent of maximum luminance. This definition results in differences in the spatial extent of the luminance change with changes in contrast and inactive area luminance.

h. Symbol subtense. The visual angle subtended by a symbol is not a variable unique to matrix displays; however, it is a variable that interacts with several of the unique matrix variables. Symbols of varying height may result from changes in emitter spacing and symbol definition. If the viewing distance remains constant and the height changes, symbol subtense will change according to the relationship given in the discussion of emitter size (paragraph 7.3.b).

i. Font. Symbol definition and type of emitter packing will impact the selection of a font.

j. Contrast. Contrast is a significant variable in matrix displays as in other display types and is defined in exactly the same way.

k. Surround luminance. The adaptation level of the eye will be determined by the luminance of the surround. Since adaptation level affects acuity, surround luminance will affect other matrix variables.

l. Inactive area luminance. In matrix displays with less than 100 percent active area, the luminance of the inactive area is a variable. If the inactive area luminance is the same as the background, only the emitters are visible. However, if the active area has the same luminance as the active emitters, then this area is perceived as part of the symbol. For intermediate values of luminance, the inactive area, on-emitters, and off-emitters are all visible.

m. Nonindependence of variables. A number of matrix display variables are not independent of one another. Emitter size, emitter spacing, percentage active emitter area, symbol definition, and symbol subtense form a nonindependent set of variables so that the level of one variable affects and constrains the possible levels of the other variables.

For example, as emitter size changes, small changes in the height of the symbol also occur. If the viewing distance remains constant, then the change in height will result in corresponding changes in the angular subtense of the symbol.

Other interdependencies can also be identified. The maximum active area that can be achieved will be determined by both emitter shape and emitter packing format as discussed previously. In turn, the percentage of active area will influence the possible ranges of other variables.

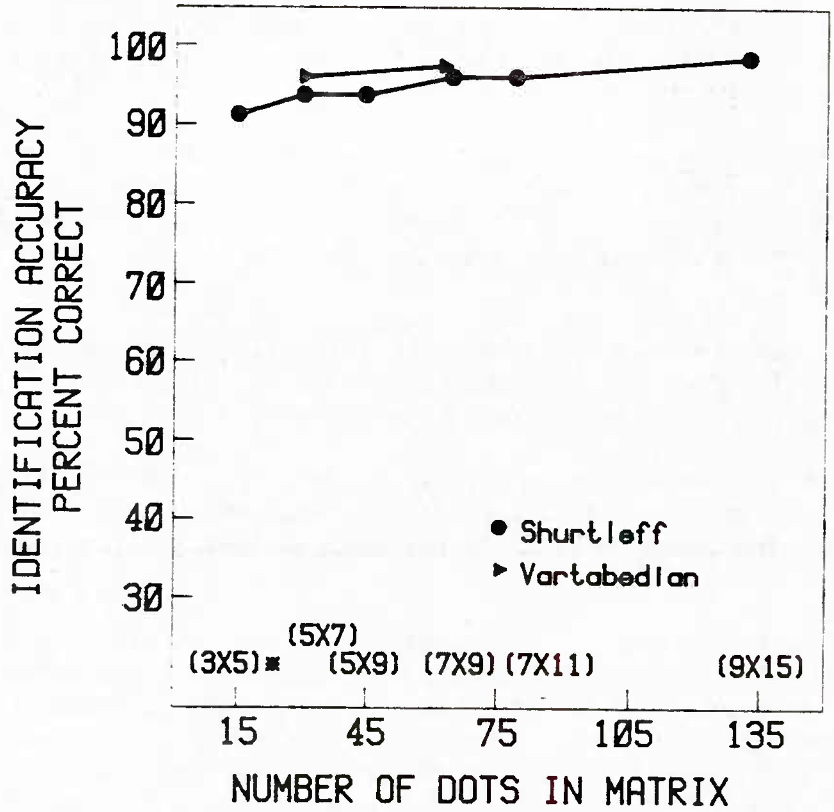
The emitter edge luminance gradient can take on a large range of values if the active area is low, but is limited to inifinity (sharp edge) if the active area is 100 percent. This follows when the physical extent of an emitter is defined as that point where the luminance is 50 percent of maximum. To attain 100 percent active area requires that the physical extent of adjacent emitters be coincident and because no emitter overlap is possible with a matrix element display, a sharp transition must result. Similarly, inactive area luminance is meaningless if all of the area is active.

The extent to which symbol font can be manipulated is determined by symbol definition. When definition is low (3 x 5 for example) very little, if any, font variations are possible. However, with a 15 x 21 symbol matrix considerable variation can be achieved.

7.4 Dot Matrix Size Effects

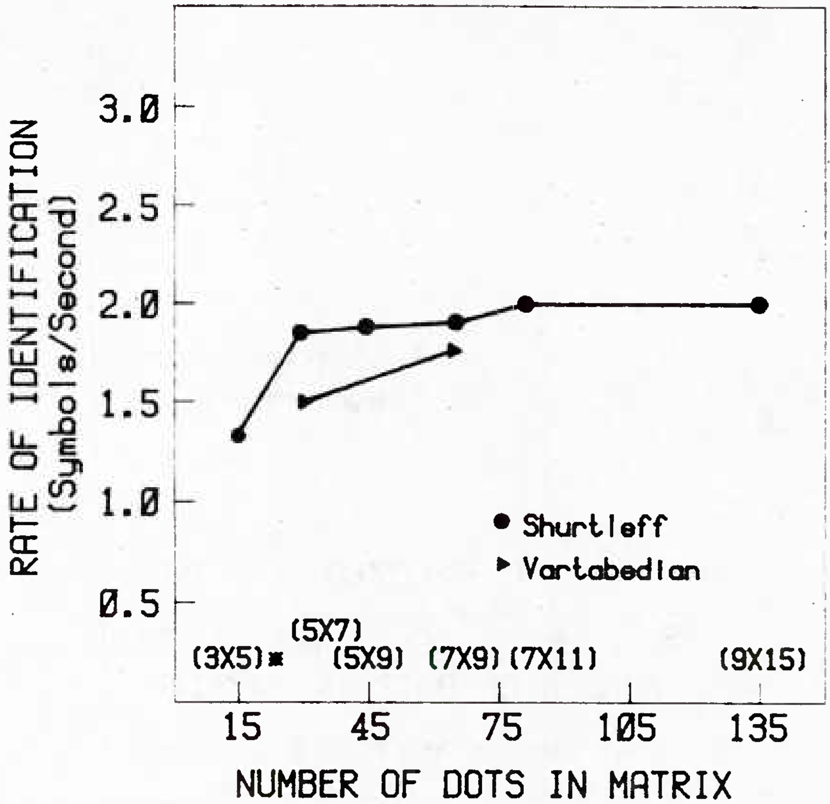
The most popular way of constructing symbols for CRT displays is from a matrix of dots. The commercial standard and the most commonly used matrix size is 5 x 7, but sizes of 9 x 15 or more may be encountered. There is little technical information available to justify selection of the 5 x 7 dot matrix as an industrial standard over other matrix sizes.

Figures 165 and 166 show the overall relationship between the number of dots used in the symbol matrix and accuracy and speed of symbol identification. Accuracy of identification gradually and very slightly decreases for resolutions smaller than 7 x 11. In the Shurtleff studies (1970a, 1970b), speed of identification decreases for resolutions smaller than 5 x 7, but is fairly uniform for greater resolutions. Vartabedian's data (1970) show a greater loss of speed of identification when the 7 x 9 matrix is reduced to a 5 x 7 matrix. Snyder (1980) recommends 7 x 9 for numerals and upper case letters in contextual material (words) and 9 x 11 for noncontextual displays. The commercial standard of a 5 x 7 matrix is marginal. To achieve accuracy greater than 95 percent, the designer should provide 7 x 9 or larger matrices.



*Number of rows and columns making up matrix.

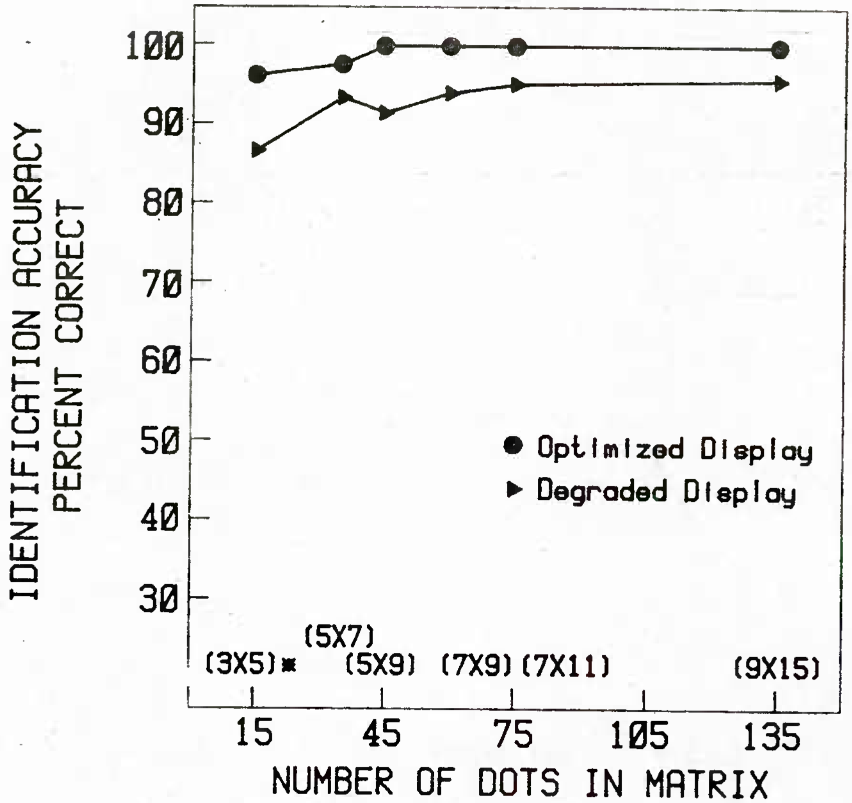
Figure 165. The relationship between number of dots in a matrix and identification accuracy.



*Number of rows and columns making up matrix.

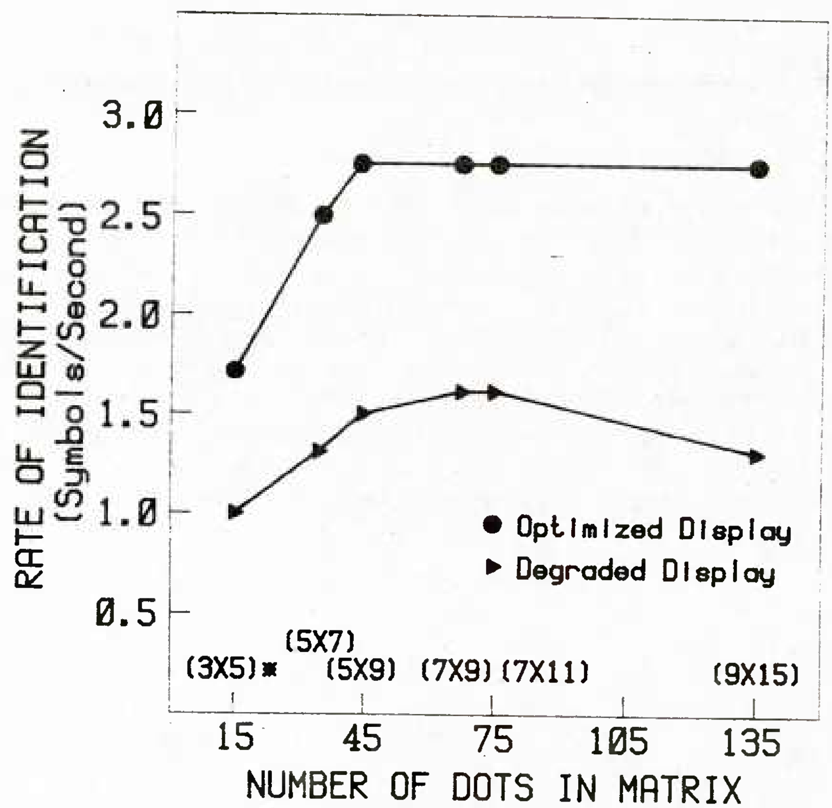
Figure 166. The relationship between number of dots in a matrix and rate of identification.

Although there are not many data on dot matrix interactions, Shurtleff (1970a, 1970b) identified some interactions that affect selection of dot matrix size. Figures 167 and 168 show interactions between dot matrix size and display quality. The degraded display condition was in the form of symbol overprinting (Shurtleff, 1970a) and by providing a small visual size (Shurtleff, 1970b). The overprinting conditions consist of one symbol superimposed over a second symbol. Overprinting is a common source of degradation in military systems (e.g., air situation displays in which aircraft flying close together in air space will often have overlapping alphanumeric tags and messages). The optimized display conditions of Figures 167 and 168 represented a display with values within the range of those recommended in the present data base.



*Number of rows and columns making up matrix.

Figure 167. The relationship between number of dots in a matrix and identification accuracy for optimized and degraded displays.



*Number of rows and columns making up matrix.

Figure 168. The relationship between number of dots in a matrix and rate of identification for optimized and degraded displays.

Figure 167 suggests that the commercial standard of 5 x 7 may be satisfactory only for good quality displays. When the display quality is impaired, Figure 167 suggests that dot-matrix size has to be 7 x 9 or larger in order to achieve an accuracy of identification of 95 percent or greater.

Figure 168 indicates that for both the optimized and the degraded display, major losses in rate of identification occur only when the matrix is smaller than the 5 x 7.

The results found by Snyder and Maddox (1978) verify Shurtleff's conclusions. In their study, three matrices (5 x 7, 7 x 9, and 9 x 11) were contrasted under two conditions, a reading task and a menu search task. Figures 169 and 170 indicate that the 5 x 7 matrix was significantly better for the reading task, but both the 7 x 9 and 9 x 11 matrices were superior for the menu search task, with the 9 x 11 being best.

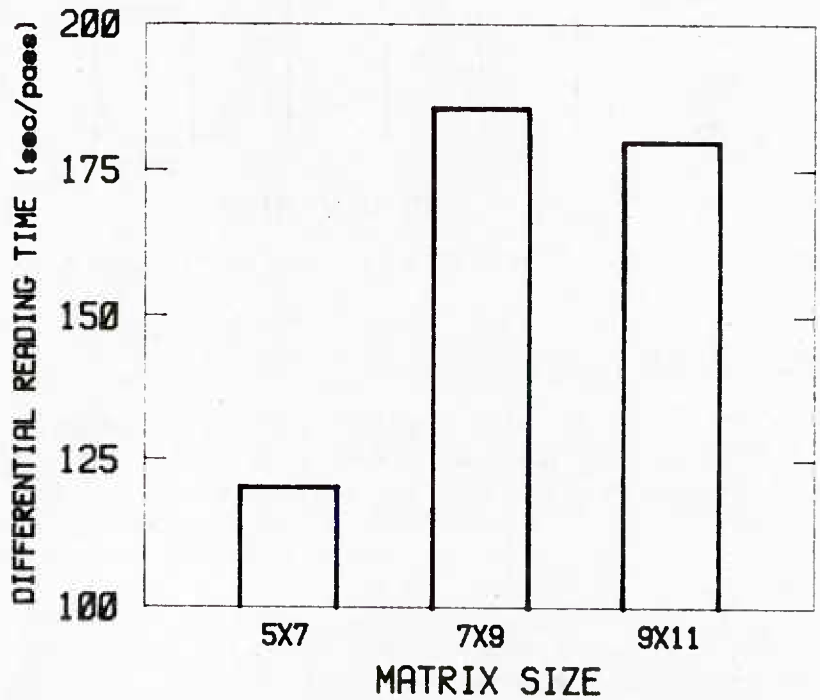


Figure 169. Effect of matrix size upon reading time (taken from Snyder & Maddox, 1978).

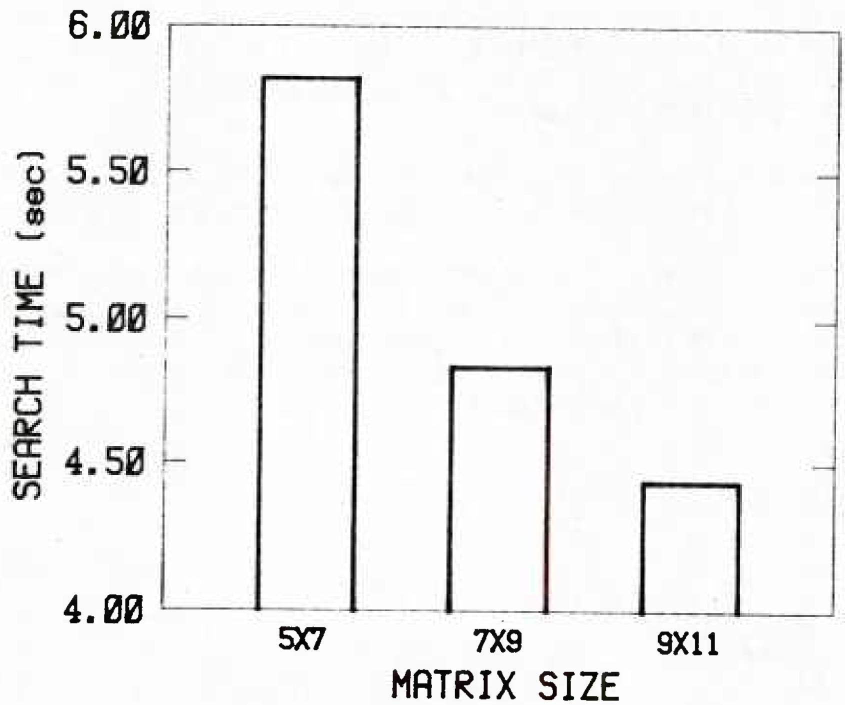


Figure 170. Effect of matrix size upon menu search time.

7.5 Dot Shape Effects

There is very little research available showing the relationship between the shape of the dot element and the speed and accuracy of symbol identification. One study (Vartabedian, 1970) compared alphanumerics constructed of circular dots with those constructed of elongated dots. The elongation of the dot was in the vertical direction making symbol constructions that were very similar in appearance to those constructed by TV raster-scan lines.

The results of the study are shown in Figures 171 and 172 where it can be seen that both accuracy and speed of response were better when the symbols were constructed with circular elements rather than with elongated elements. This finding is not surprising since, as indicated earlier, the symbols constructed with elongated dots resemble TV constructions and 10 to 12 scan lines per symbol height are needed to maximize speed and accuracy of identification.

Other researchers have indicated that circles and square elements in dot matrices are superior to shapes such as rectangles, diamonds, or triangles (Buckler, 1977; Semple et al., 1971; Vanderkolk et al., 1975), but there is little objective evidence to support this contention. Snyder and Maddox (1978) contrasted a square shape with horizontal and vertical elongated shapes. Their results, shown in Figures 173 and 174, indicate that the square shape was significantly superior to the elongated shapes in terms of both reading time and random search time.

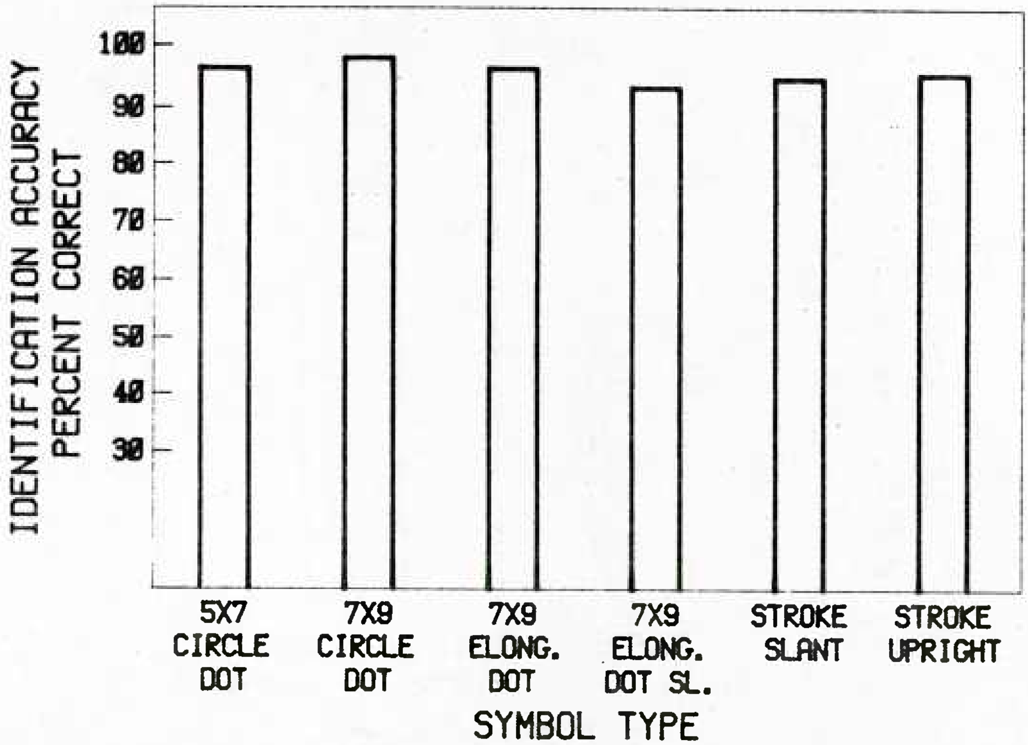


Figure 171. Accuracy as a function of six different methods of forming symbols.

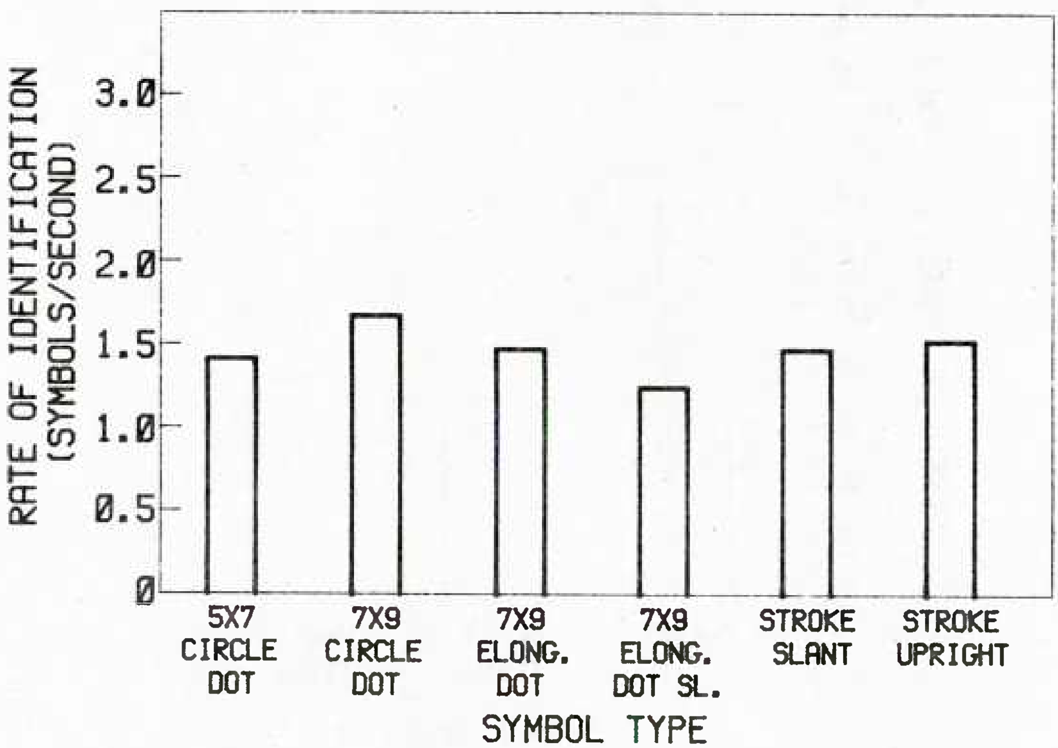


Figure 172. Rate of identification as a function of six different methods of forming symbols.

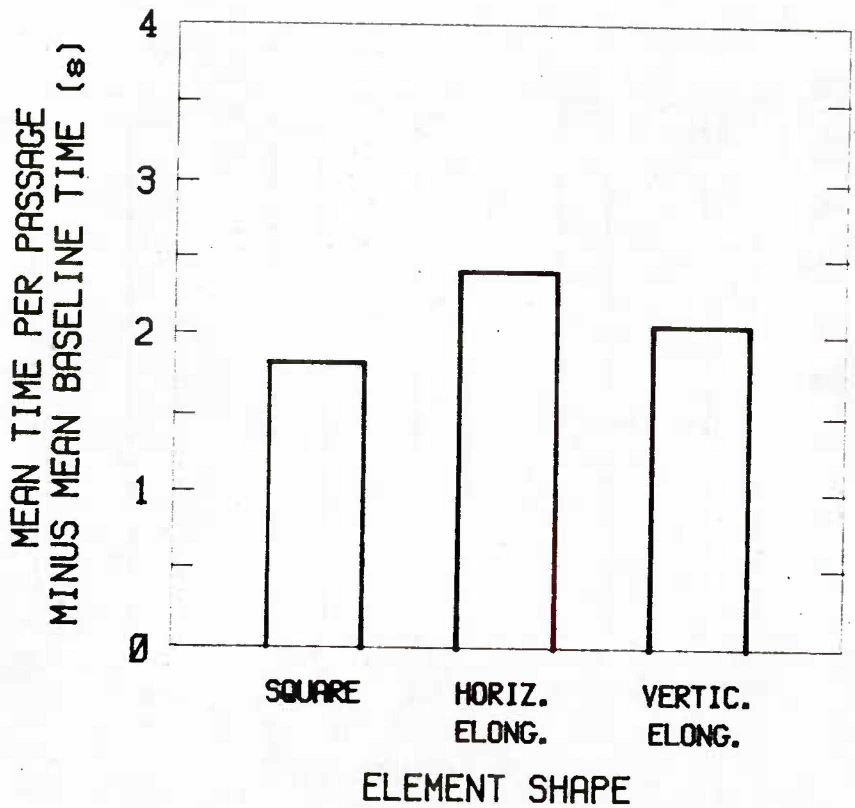


Figure 173. Effect of element shape on reading time (taken from Snyder & Maddox, 1978).

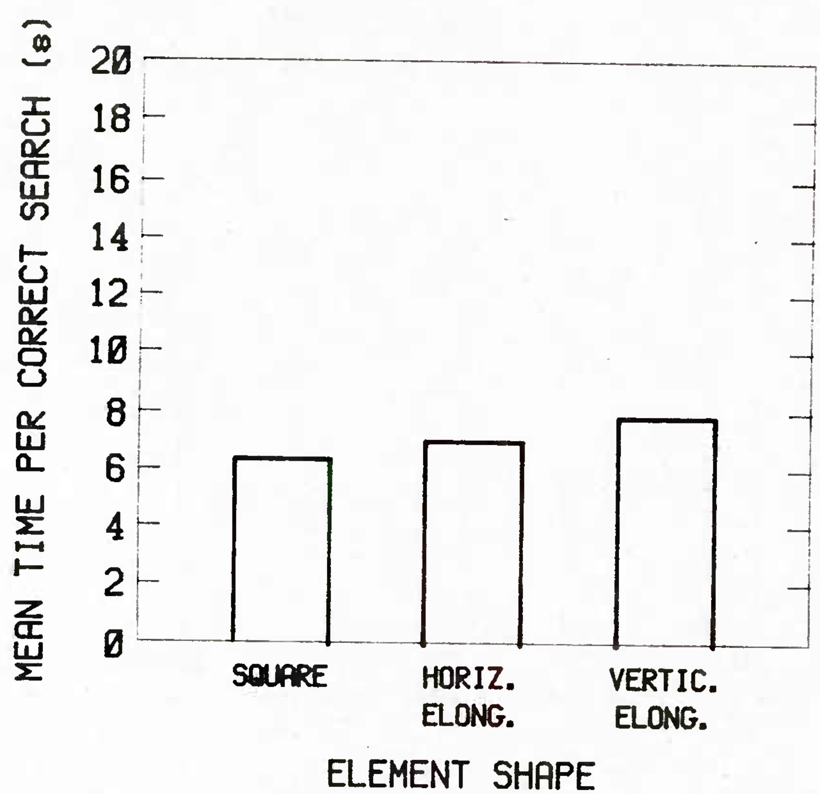


Figure 174. Effect of element shape upon random search time (taken from Snyder & Maddox, 1978).

7.6 Dot Spacing Effects

The effects of dot spacing on accuracy and speed of symbol identification is a function of the percent active area. Percent active area is a concept that describes the proportion of a symbol actually emitting light. It is defined as

$$\left(\frac{\text{emitter size}}{\text{emitter space}}\right)^2 \times 100. \tag{7.2}$$

It can be increased by increasing emitter size or decreasing spacing between elements, assuming subtense is held constant. Increased active versus inactive bandwidth results in improved legibility.

With dot-matrix displays, research has found that decreasing the space between active elements results in improved legibility (Buckler, 1977). Larger, dimmer dots were found to give better legibility than smaller, brighter dots (15% in Buckler, 1977). Vanderkolk et al. (1975) found that, when they contrasted an active area of 64 percent with one that was only 11 percent, performance was severely decremented: Average time to recognize was 4.3 seconds when the active area was 11 percent as opposed to 1.5 seconds when the active area was 64 percent. A second study indicated that as the active area is reduced, contrast must increase. For the center range of surround luminance (5 to 500 fL), the required contrast as a function of active area is independent of surround luminance. Scanlan and Carel (1976) reported the rate of symbol identification drops from about 160 to 120 per minute as the active area is reduced (value unspecified).

Spacing between elements should be sufficiently close that the observer cannot detect gaps in the constructions of symbols and that the symbol stroke appear as visually fused, continuous strokes (Botha & Shurtleff, 1963; Buckler, 1977; Vartabedian, 1971). Objective evidence to support the notion that minimum gaps and continuity of stroke are important factors in the identification of symbols comes from a study of simulated TV constructions of symbols by Botha and Shurtleff (1963). In that study, the ratio of the width of the active TV line to the width of the inactive TV line was varied and related to identification performance. Three ratios were studied, 1:2, 1:1, 2:1. As Figures 175 and 176 show, accuracy and speed of identification improved as the continuity of symbol stroke improved by increasing the width of the active element and decreasing the dead space between elements making up symbol strokes.

Snyder and Maddox (1978) found that, as the interelement spacing ratio increased from .5 to 1.0 to 1.5, time required for reading a passage of words also increased significantly (see Figure 177). Spacing between the elements making up the dot symbols should therefore be minimized as much as possible in order to preserve the continuity of symbol strokes.

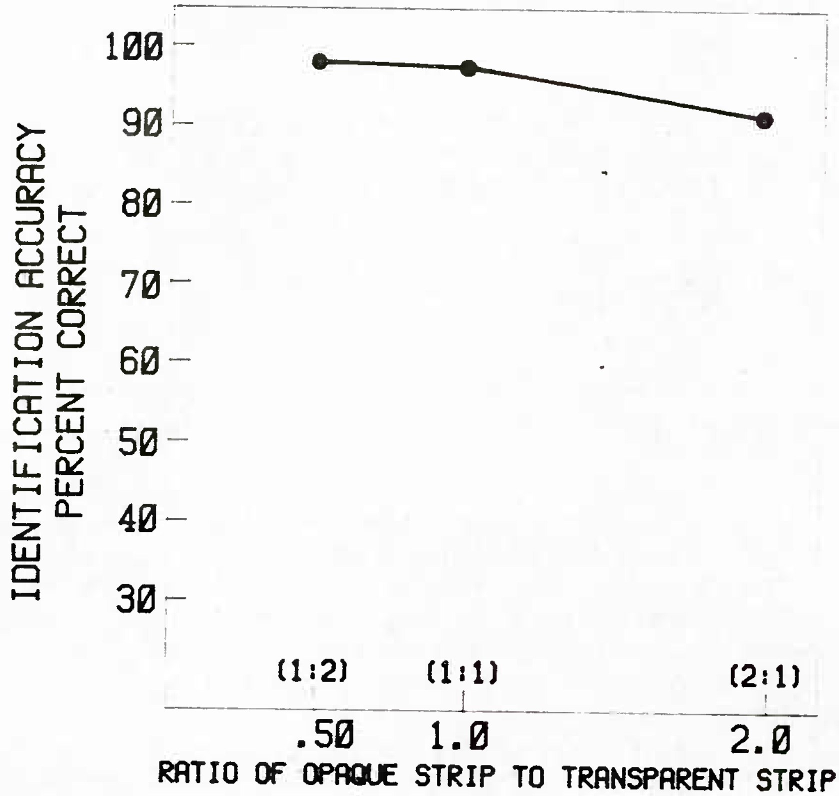


Figure 175. Relationship between ratio of active to inactive elements and accuracy of symbol identification.

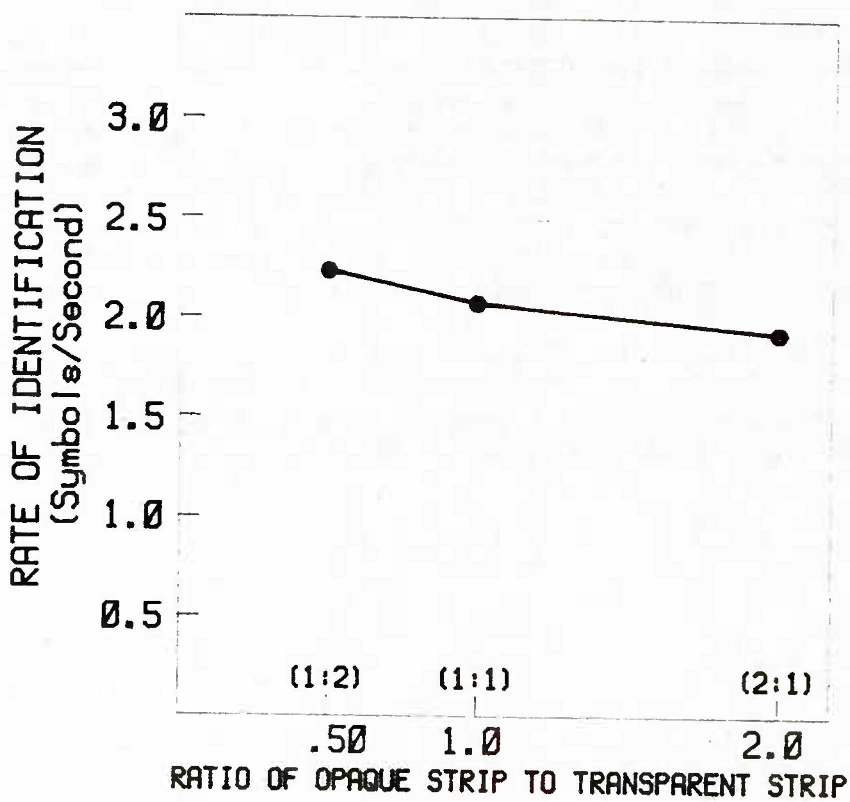


Figure 176. Relationship between ratio of active to inactive elements and rate of symbol identification.

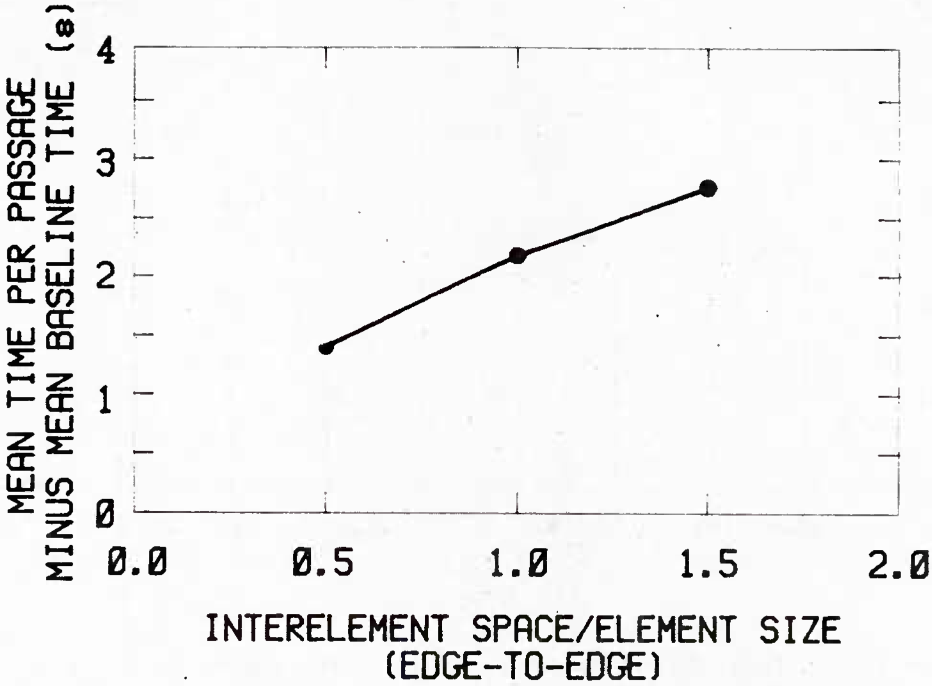


Figure 177. Effect of interelement spacing ratio upon reading time.

7.7 Differences in Dot Matrix Fonts

The evidence for major differences among matrix fonts in terms of observer performance differences is mixed. Shurtleff (1969) compared four fonts constructed in a 5 x 7 dot matrix under both ideal and degraded viewing conditions (visual size reduced to 7 minutes of arc). The four fonts, including the Lincoln/Mitre, represented samples of commercial, printing, command and control, and machine readable fonts. The results for both optimal and degraded conditions showed no statistically significant differences among the four fonts.

A more recent evaluation by Maddox, Burnette, and Gutmann (1977) compared the Lincoln/Mitre font with two experimental fonts. The symbol was exposed for 40 milliseconds and was then overprinted with a full 5 x 7 matrix of dots. The results of this study were that the absolute differences among all three fonts were within 2 to 3 percent. In somewhat of a reversal of the previous results, Snyder and Maddox (1978) found that the fairly well known Huddleston and Lincoln/Mitre fonts were superior to two experimental fonts, one emphasizing maximum number of dots; the other, maximum angle of display (Figure 178).

The Lincoln/Mitre or Huddleston font in a 7 x 9 dot matrix might well be the best choice for the designer.

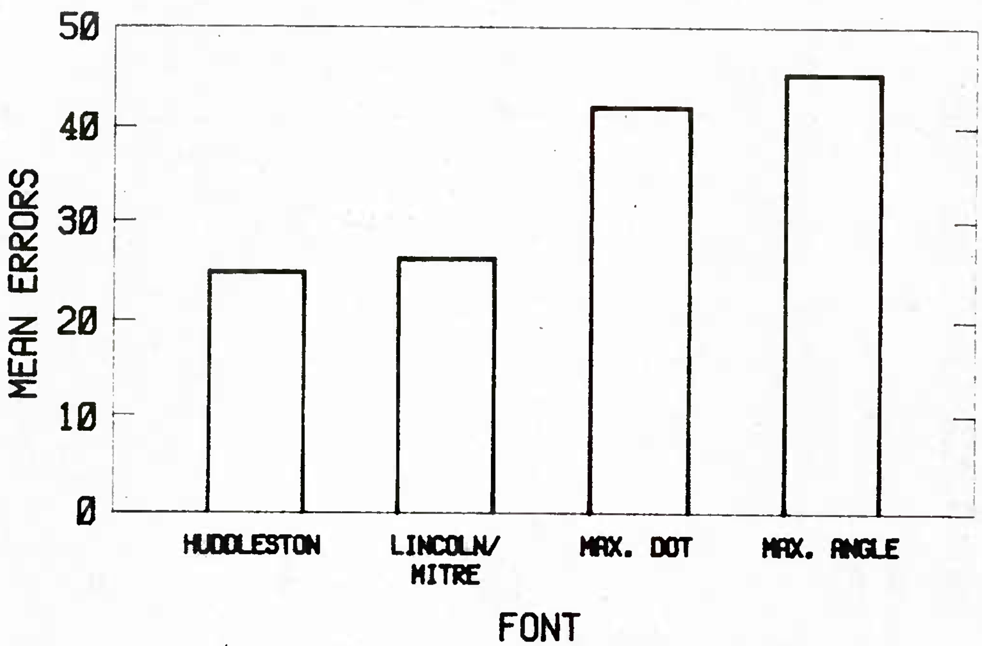


Figure 178. Effect of font upon number of errors (taken from Snyder & Maddox, 1978).

7.8 Other Dot Matrix Display Parameters

a. Character size. Snyder and Maddox (1978) found that, as expected, accuracy in reading symbols increased and response time decreased significantly as a function of character size (Figures 179 and 180) and that character size interacts with luminance (Figure 181), view distance (Figure 182), and exposure time (Figures 183 and 184).

b. Dot size. The size of the elements in the matrix character have been shown by Snyder and Maddox (1978) to have an effect in reading and random search tasks and must therefore be considered by the designer. Smaller dots were more favorable to quick scanning with redundant cues (the reading task), while simple detectability was enhanced in search tasks by using the larger elements. This is shown in Figures 185, 186, and 187. That illuminance interacts with element size is shown in Figure 188.

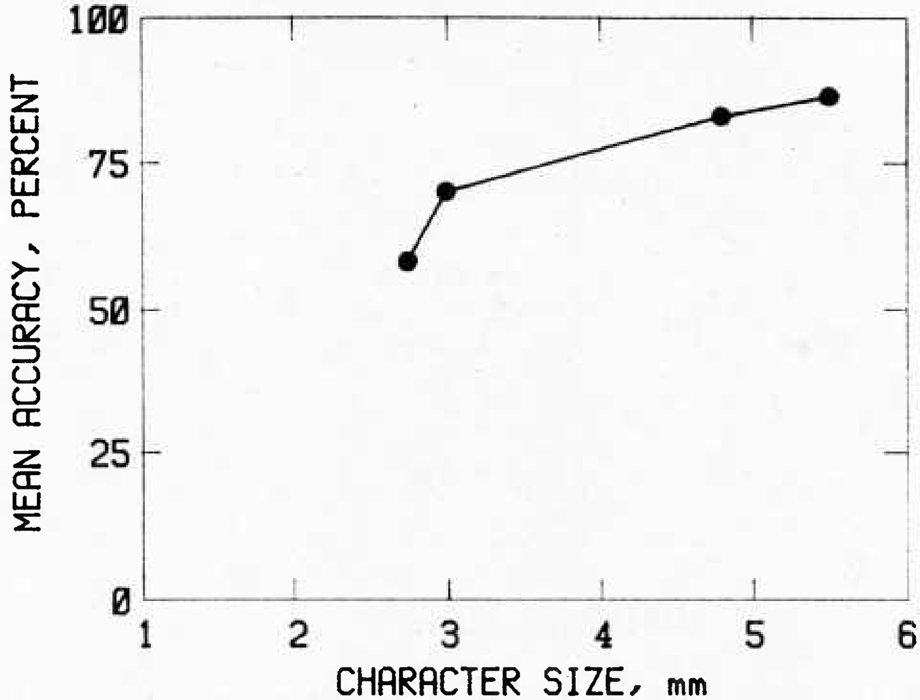


Figure 179. Effect of character size upon accuracy.

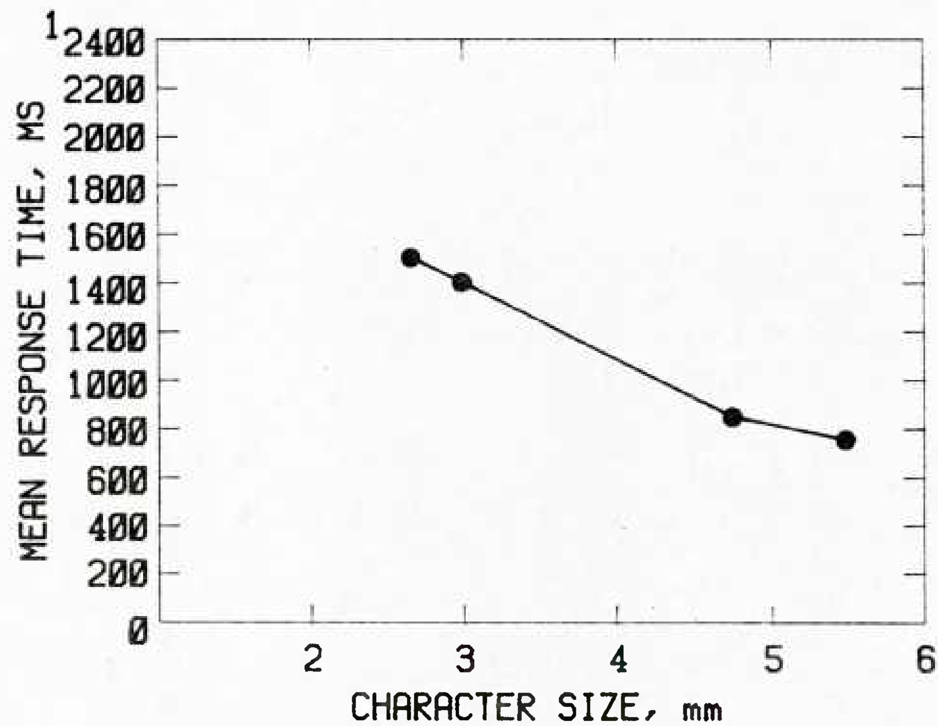


Figure 180. Effect of character size upon response time.

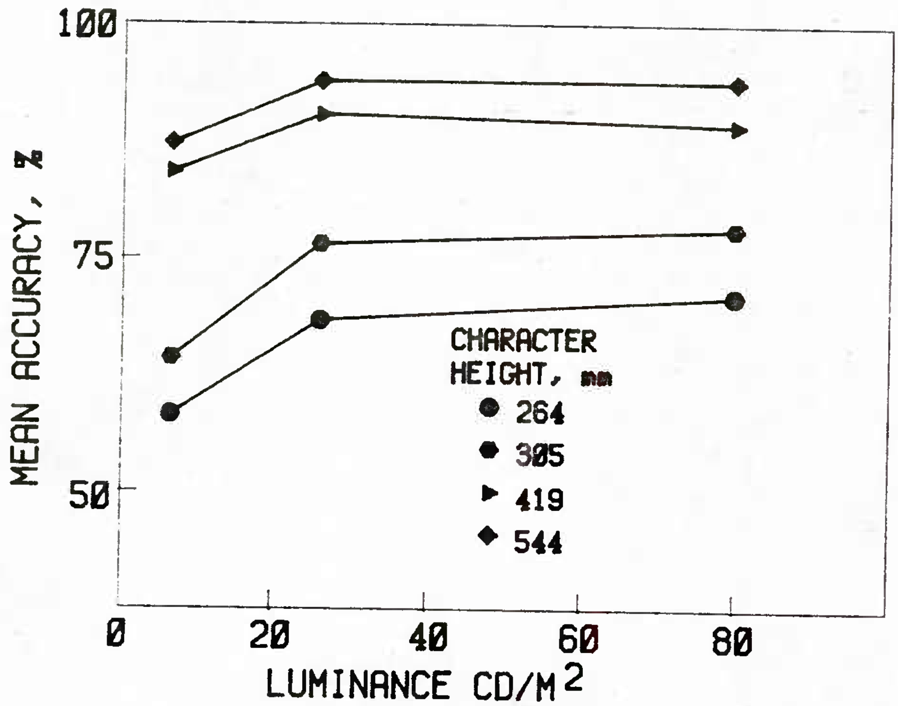


Figure 181. Effect of character size by luminance interaction upon accuracy.

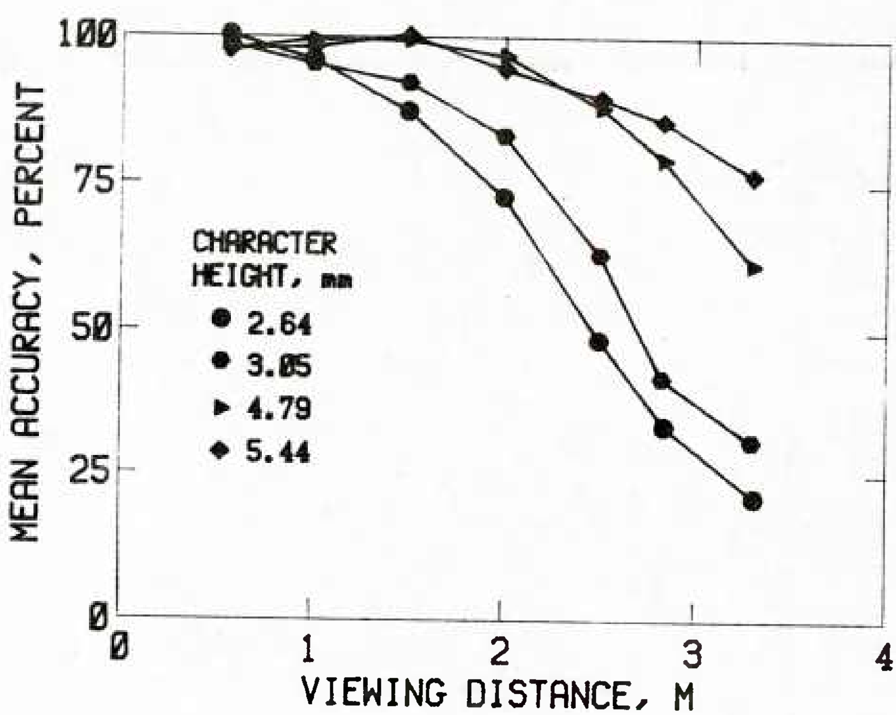


Figure 182. Effect of character size upon accuracy at various viewing distances.

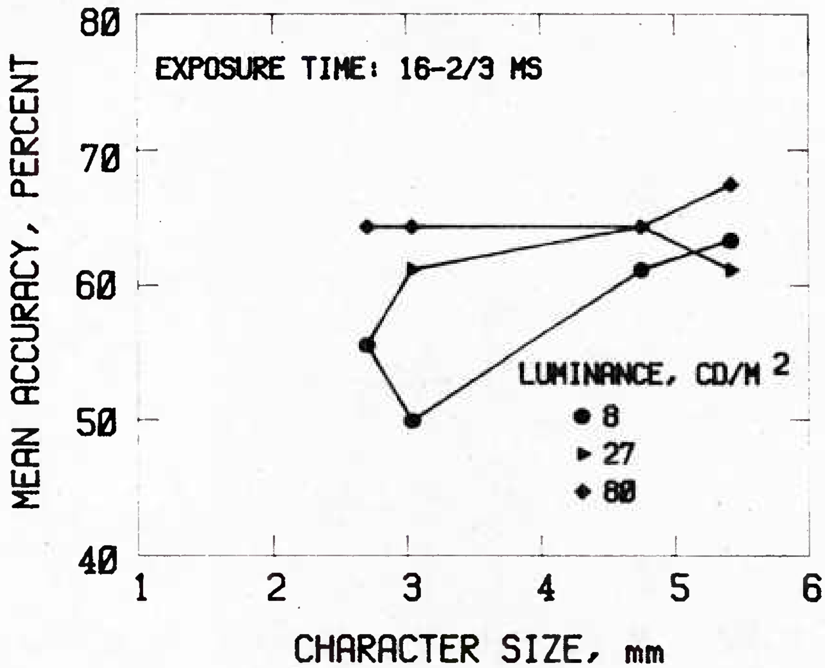


Figure 183. Effect of character size by luminance interaction at 16.67 millisecond exposure time.

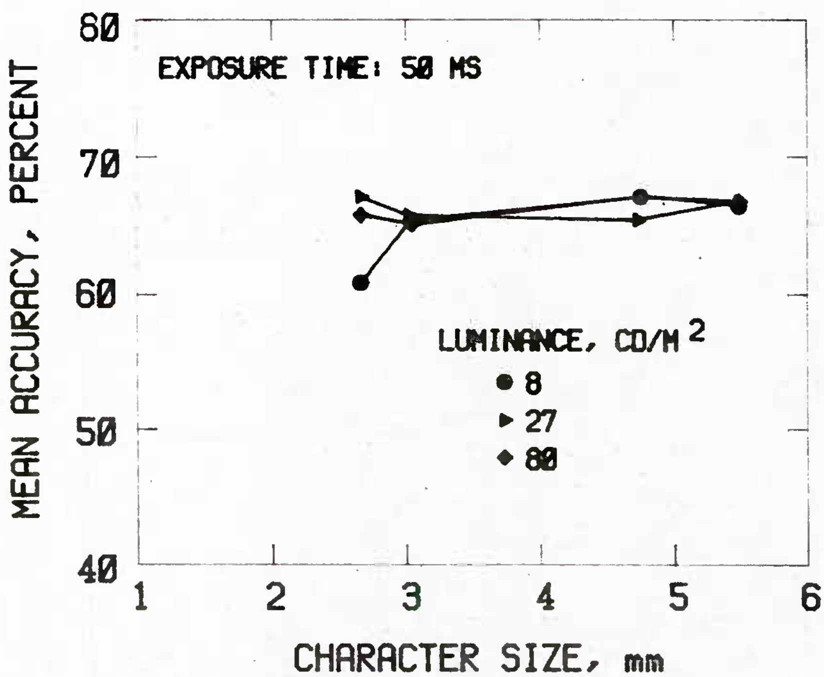


Figure 184. Effect of character size by luminance interaction at 50 millisecond exposure time.

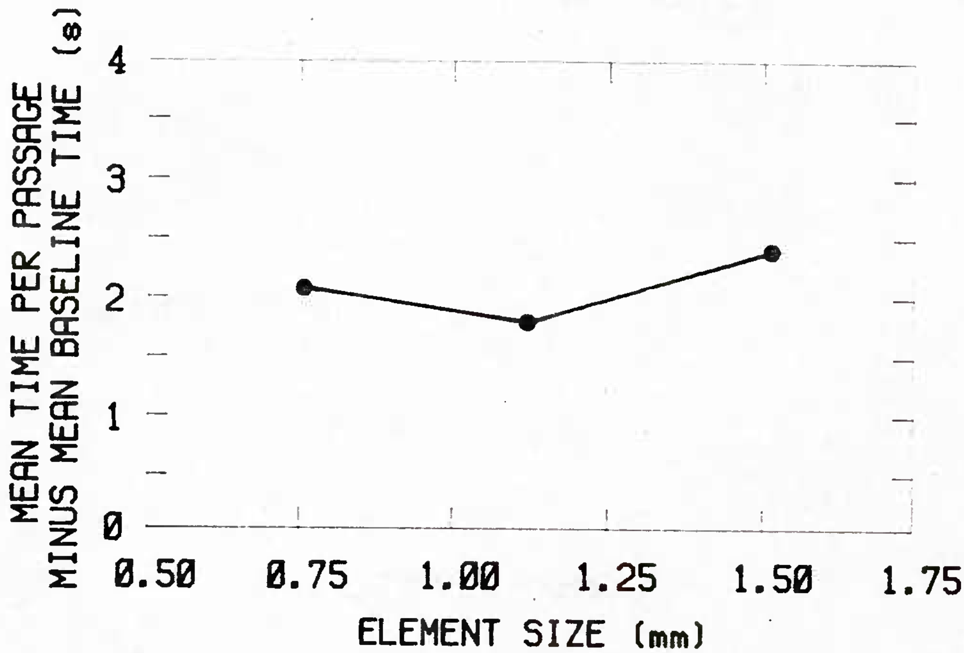


Figure 185. Effect of element size on reading time.

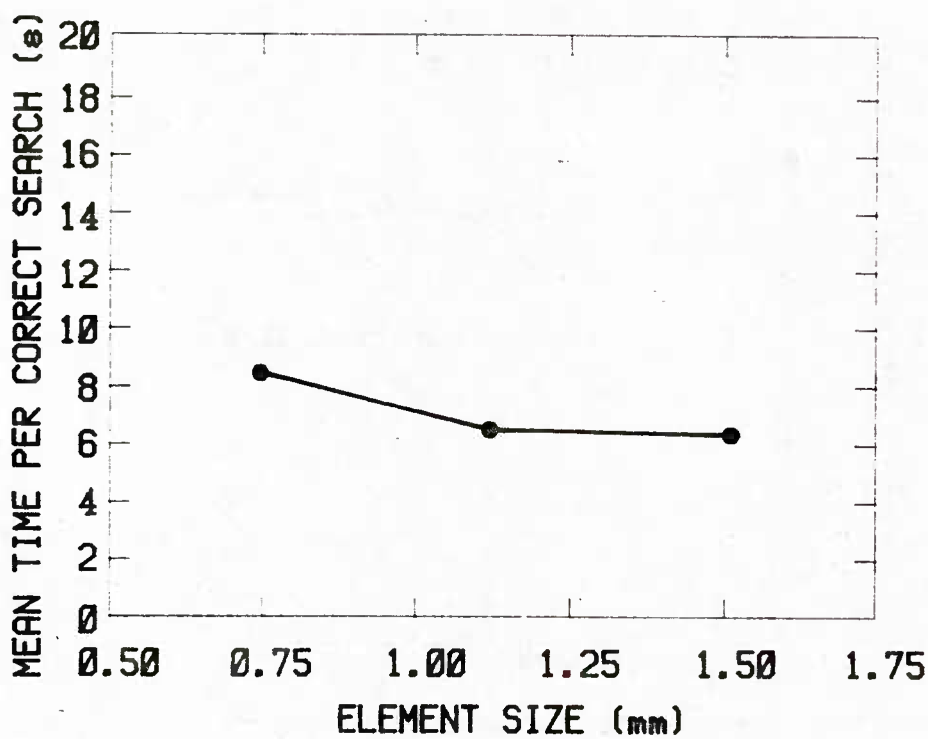


Figure 186. Effect of element size upon random search time.

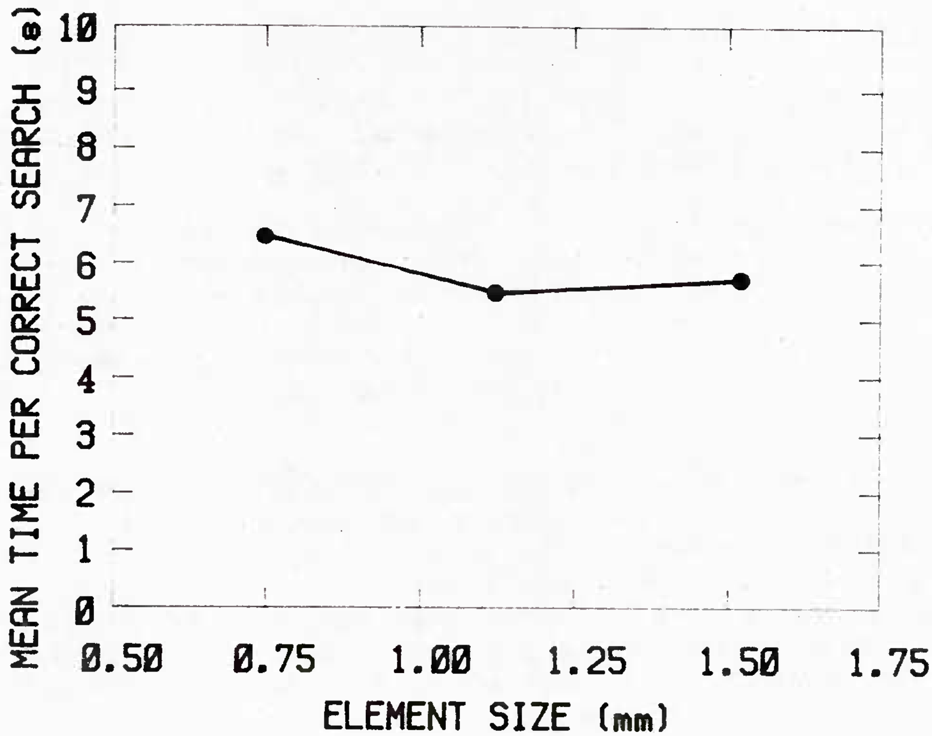


Figure 187. Effect of element size upon menu search time.

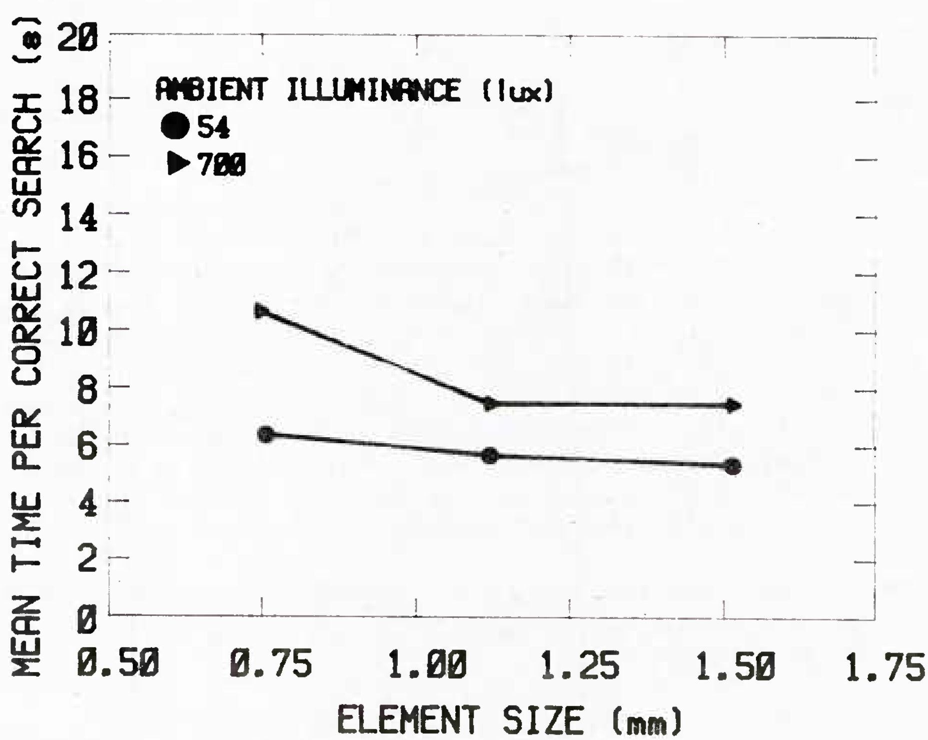


Figure 188. Effect of element size by illuminance interaction upon random search time.

7.9 Stroke Matrix Size Effects

A second popular technique for CRT displays is to form symbols from stroke elements. Two techniques are currently widespread--one using a fixed-position matrix of strokes, the other using a "random-position" stroke matrix.

The fixed-position matrix technique provides different numbers of elements to construct symbols. For example, fixed-position matrix elements can vary from as few as seven "bar-matrix" elements provided for numeric displays to as many as 16 "starburst" elements provided for alphanumeric displays. Random-position matrices vary in the number of points within a matrix between which strokes can be drawn to form symbols. The number of points can vary from as few as a 4 x 4 matrix of points to as many as a 9 x 9 matrix of points or more.

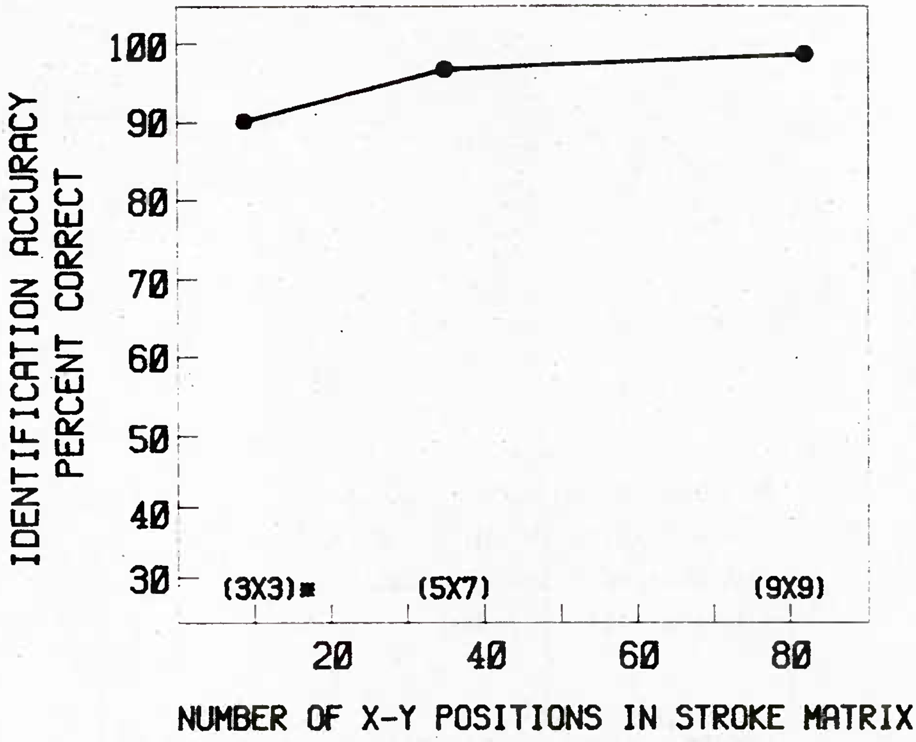
A preliminary estimate of the relationships existing between number of X-Y positions in a stroke matrix and accuracy and speed of identification is shown in Figures 189 and 190 (Shurtleff, 1970c). Both rate and accuracy of identification show essentially the same relationship; namely an almost imperceptible decline in performance for X-Y positions from 9 x 9 to 5 x 7 and a steeper decline for X-Y positions from 5 x 7 to 3 x 3. The form of the relationship is strikingly similar to that found for dot-matrix elements. The relationship is retained when the display is degraded by overprinting. Therefore, a stroke matrix, as a minimum, should provide a 5 x 7 set of X-Y positions within which symbols can be generated, if the designer wishes to have accuracy of symbol identification of 95 percent or better. The 5 x 7, X-Y positions are acceptable for forming symbols when display conditions are optimal (i.e., correspond to the criteria in this data base), but the larger 9 x 9, X-Y positions may provide more accurate symbol identification if display degradation is known or anticipated.

7.10 Dot Matrix vs. Stroke Matrix

Display designers may ask which displays are more legible--those with symbols constructed by dot-matrix elements or those constructed by stroke-matrix. To answer this question, some comparative studies have been performed.

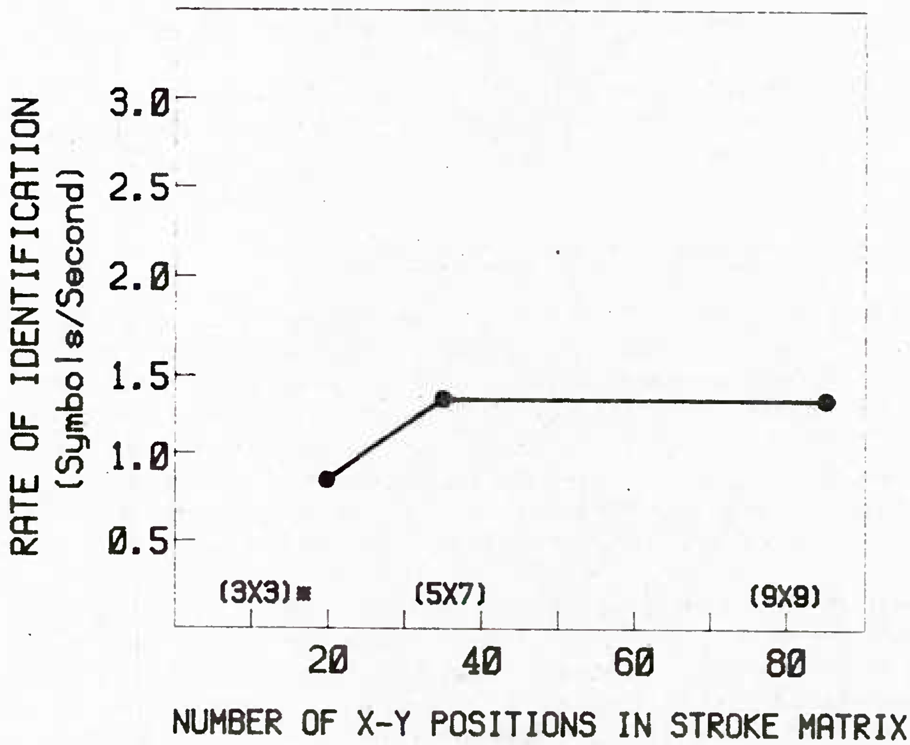
Vartabedian (1970) concluded that dot-matrix symbols are superior in legibility. In order for such a conclusion to be meaningful, the comparison must be made under identical conditions except for the single variable--the method of symbol construction. The symbols must approximate a common standard or be designed to a common style or font. If this is not done, style differences (i.e., those not caused by inherent limitations of the construction technique itself) may bias the results. According to Shurtleff (1980), this is what happened. Shurtleff (1970c) came close to meeting these conditions. Figure 191 shows that similar relationships are manifested for both types of symbols. Only under degraded display conditions are there differences in the relationships between dot and stroke symbols--and hence, the evidence favors stroke symbols.

It appears, therefore, that for, general display applications, either stroke or dot symbols are acceptable. If degraded display conditions are anticipated, designers might want to provide stroke-matrix symbols.



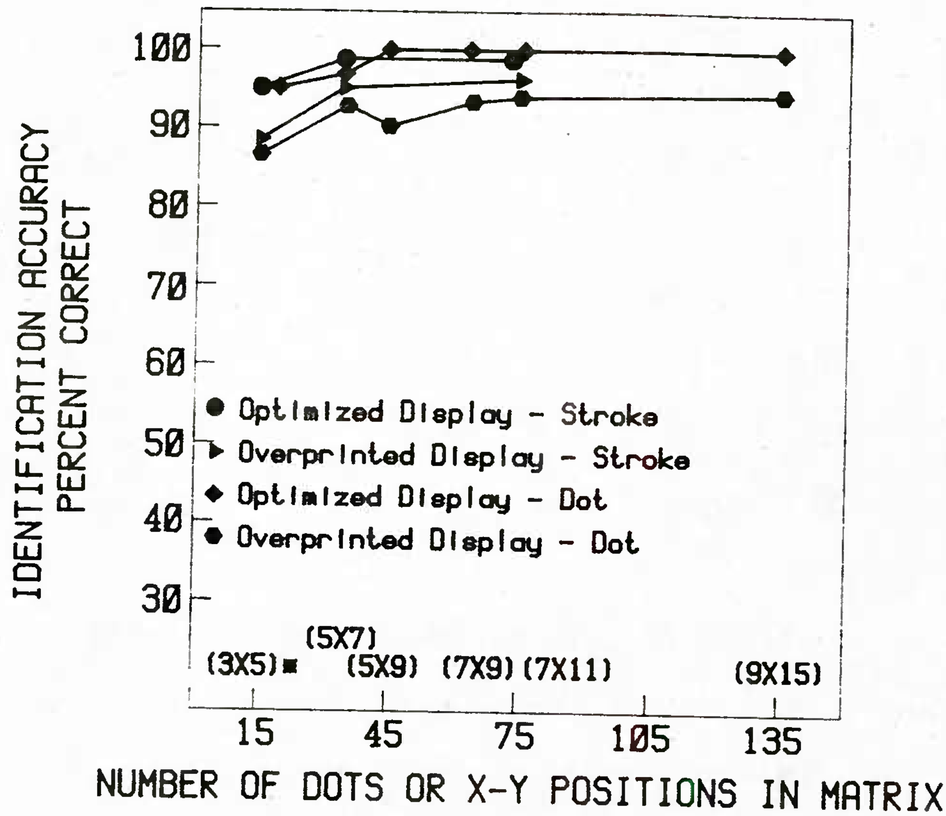
*Number of X-Y positions within which symbols can be generated.

Figure 189. Relationship between number of X-Y positions in a stroke matrix and identification accuracy.



*Number of X-Y positions within which symbols can be generated.

Figure 190. Functional relationship between number of X-Y positions in a stroke matrix and rate of identification.



*Number of rows and columns making up matrix.

Figure 191. Relationships between number of elements for dots, number of X-Y positions for strokes, and identification accuracy.

7.11 Effect of Luminance Upon Symbol Legibility

According to Gould (1968), any display luminance of about 68 cd per m^2 is probably adequate, assuming that the ambient illuminance is such that sufficient modulation is maintained between the displayed characters and their background. The results found by Snyder and Maddox (1978) are relatively consistent with this recommendation. In their study, accuracy decreased and response time increased significantly when the mean character (display) luminance was decreased from 27 to 8 cd per m^2. Accuracy and response time did not improve significantly when luminance was increased beyond 27 cd per m^2. Their results are depicted in Figures 192, 193, and 194.

In their studies, luminance became critical only at the two smaller character sizes they used; conversely, character size became significant only when luminance dropped as low as 8 cd per m^2. Recognition of letters is affected strongly by luminance only when the letters subtend 17 minutes of arc or less (2.64 and 3.05 mm). At character sizes of 27 minutes and above (4.79 and 5.44 mm), luminance played a less important role. For small character sizes, increases in luminance typically improved performance, with the difference decreasing as character size increased. There is an interaction with viewing distance; the effect is significant at viewing distances greater than 1.5 m but it is insignificant at lesser viewing distances.

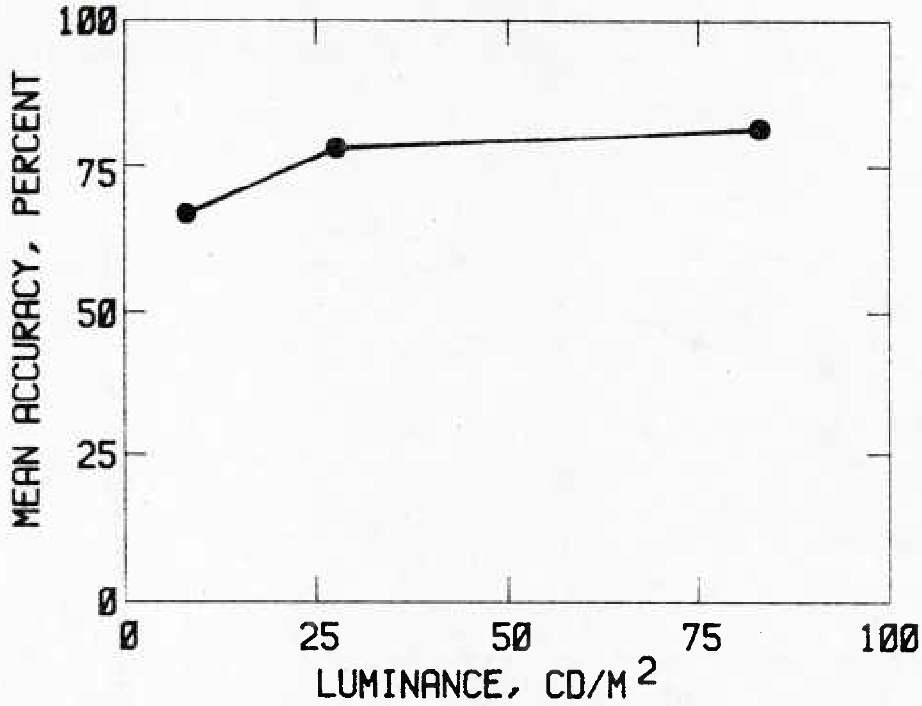


Figure 192. Effect of luminance upon accuracy.

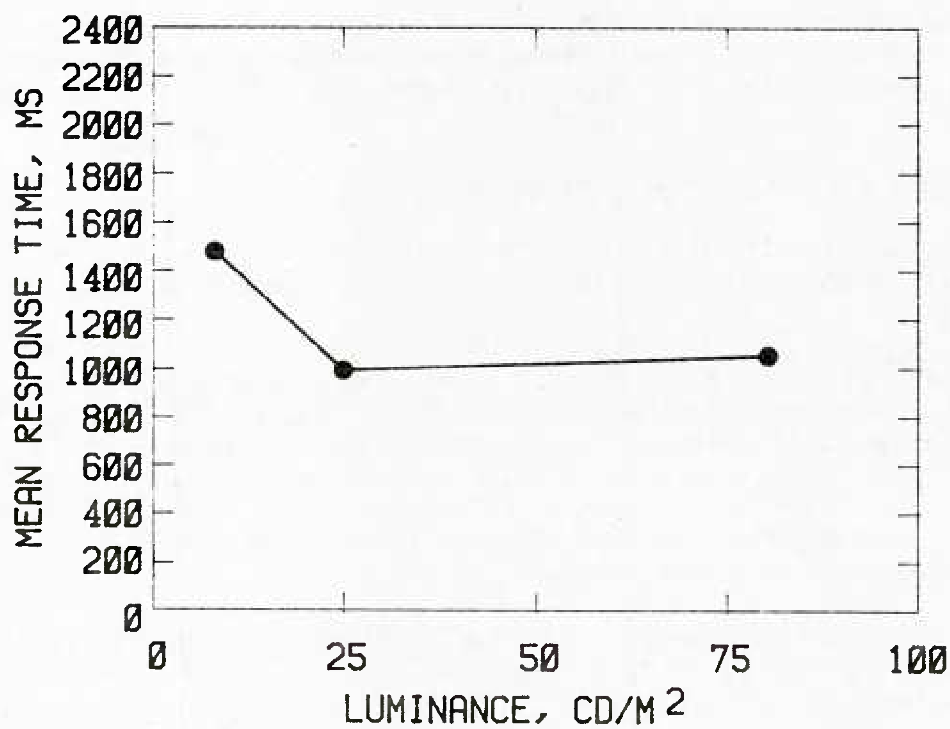


Figure 193. Effect of luminance upon response time.

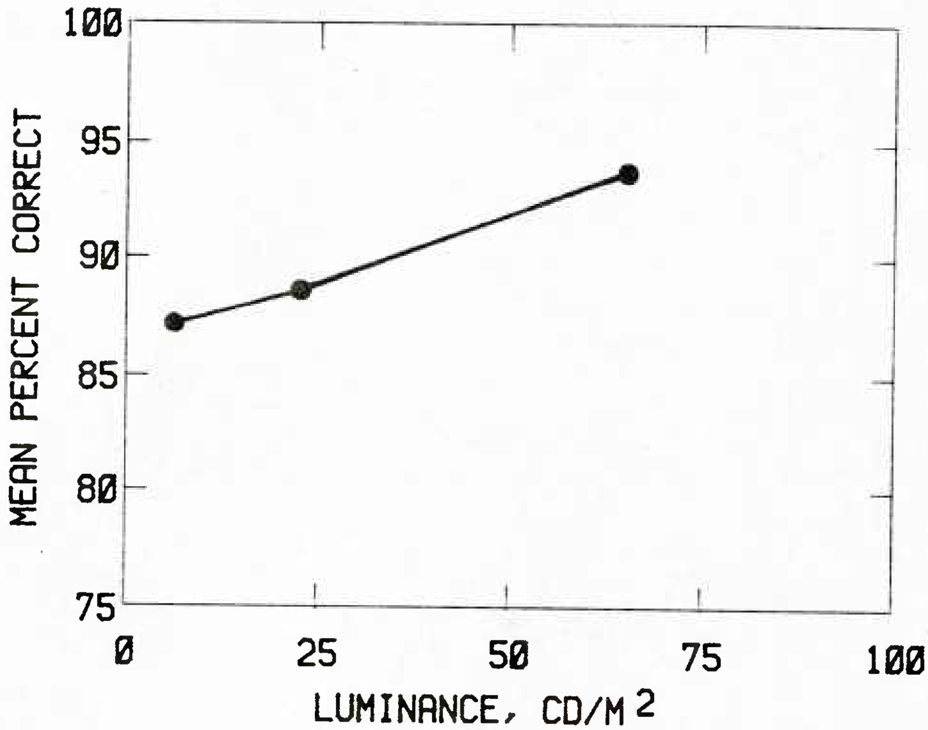


Figure 194. Effect of luminance upon anagram scores.

By increasing luminance, response accuracy can generally be increased. To overcome the adverse effects of small character size, luminance should be increased and conversely, to overcome the adverse effects of low luminance levels, character size should be increased.

7.12 Summary and Design Recommendations

Snyder and Maddox (1978) have reviewed and commented on the literature describing dot-matrix parameters. The following is taken from their report:

a. Character size. Howell and Kraft (1959) recommended character sizes of at least 12 minutes of arc for 85 percent character recognition and 16.4 minutes of arc for 97 percent recognition for single, clearly defined, nonblurred characters having a modulation of at least 88 percent. Shurtleff (1974) and Giddings (1972) similarly recommended 22 and 21.5 minutes of arc angular subtense, respectively, as being optimal, although Howell and Kraft (1959) indicated 27 minutes of arc was needed for blurred characters and Shurtleff, Marsetta, and Showman (1966) suggested 36 minutes of arc might be needed for raster-scan characters.

The results of Snyder and Maddox (1978) indicate to them that, for high modulation characters, no further improvements are obtained beyond 11 minutes of arc for single character recognition in a known display location. If the modulation is reduced to about 40 percent, then larger (e.g., 17 arc minute) characters are needed even if there is some contextual effect.

To minimize reading times, 25 minutes of arc seems maximal for character vertical subtense. To minimize search time, however, larger characters prove better.

b. Dot size. Snyder and Maddox (1978) indicate that smaller dot sizes (e.g., .76 mm) are best for reading contextual material, while larger dots (and, therefore, generally larger characters) are best for search tasks. A 1.5 mm dot is better for a search task than is a .75 mm dot, while the converse is true for a reading task. A reasonable compromise, if the display is to be used for both types of task, is a dot with diameter on the order of 1.0 to 1.2 mm.

c. Dot shape. The more square the dot is, the better the observer can perform reading, search, and single character recognition tasks. Elongated dots are measurably poorer.

d. Dot spacing. The results of Snyder and Maddox (1978) clearly indicate that performance increases as interdot spacing decreases. A dot spacing/size ratio of .5 is superior to one of 1.0 or 1.5. This result essentially agrees with that of Ellis, Burrell, Wharf, and Harokins (1975), who found that performance was better with a .5 ratio than with a 1.0 ratio. In general, the data suggest that the closer a dot matrix character approximates a continuous stroke character, the better will be the observer's performance.

e. Dot luminance/modulation. Dot luminance and modulation are, of course, not independent of one another or of the ambient illuminance. What matters most to the visual system, for the most part, is the dot modulation, as long as its luminance is above a reasonable level, say 25 cd per m^2.

Howell and Kraft (1959) recommended a modulation of 94 percent, but suggested that 88 percent was acceptable. Snyder and Maddox (1978) indicate that 75 percent modulation for words (letters in context) is equivalent to about 90 percent for noncontextual material. Thus, single symbols and characters must have higher modulation to be 85 percent recognizable than must partially redundant characters. In high ambient conditions, appropriately designed filters and glare shields become mandatory. If ambient illuminance is controllable, a relatively low level of 20 to 50 lux is desirable for maximum display information transfer.

f. Font selection. For Snyder and Maddox, the Huddleston font is superior to other fonts for a relatively small (14.4 arc minute) 5 x 7 matrix, but the Lincoln/Mitre font is preferred for larger matrix of the same or larger character size (up to 22.9 arc minutes). These results apply only to capital letters and numerals. If both upper and lower case letters are required, a matrix larger than 5 x 7 is required to display the descenders on the letters g, j, p, q, and y. Larger matrices are also required for some symbols, subscripts, superscripts, italics, and perhaps other unique needs. It is apparent that a single point design is quite unlikely to be optimal for various observer tasks; rather, the display should be optimized for the type of task required of the user. Design recommendations, on a variable-by-variable basis, are given in Table 44. As in all design recommendations, these values are not defensible to better than 10 percent or so. They should be applied intelligently to any given design application with a full understanding of appropriate human engineering, component design, and system integration principles.

Table 44

Design Recommendations for Dot-matrix Displays
(Taken from Snyder & Maddox, 1978)

Variable	Contextual Display	Noncontextual Display
Dot size [a]	0.75 mm	1.2 to 1.5 mm
Dot shape	Square	Square
Dot spacing/size ratio	≤ 0.5	≤ 0.5
Matrix size [b]	7 x 9	9 x 11
Character size [a]	16 to 25 arc minutes	1.0 to 1.2 arc degree
Dot luminance	≥ 20 cd/m^2	≥ 30 cd/m^2
Dot modulation	$\geq 75\%$	$\geq 90\%$
Ambient illuminance	≤ 125 lux	≤ 75 lux
Font [b]	Lincoln/Mitre	Lincoln/Mitre

[a] Assumes given levels of other variables.
[b] Numerals and upper case letters only.

SECTION 8

CODING OF SYMBOLS

8.0 CODING OF SYMBOLS

8.1 Introduction

Coding is putting information in symbolic form to increase the amount of information supplied while minimizing display space.

8.2 Coding Requirements and Criteria

Coding requirements differ for:

a. Projected displays (i.e., CRT and slide projected displays) and
b. Indicator displays (i.e., indicators, legend lights, and meters)

and as a function of mission requirements.

Coding should be used when:

a. Much information must be presented in a single display (100 or more characters).

b. The observer's task may be difficult (e.g. 10% complexity--percent of characters that must be discriminated).

c. The observer must respond quickly:

(1) In less than 10 seconds--when coding is required.
(2) Within 10 to 20 seconds--when coding is desirable.

Particular attention has been given to color coding. Codes should be:

a. Visible.
b. Legible.
c. Discriminable (observers must be capable of distinguishing between two or more characters).

8.3 Questions to Be Asked Before Coding

a. Optimum characteristics. What is the optimum shape, color, etc. for the code to assume? All the parameters that are expected to interact with the symbol to be coded should be considered in the selection procedure (e.g., the amount of dynamic change present or expected the criticality of the information, the presence or absence of other symbols, the effects of rapidly changing luminance levels).

b. Number of categories. How many discrete symbols will be required to provide the necessary information in symbolic form? Different alphabets have definite size limitations.

c. Minimum amount of information. What is the least amount of information that can be presented and still successfully perform the mission? If possible, a symbol type and alphabet should be selected in which a single meaning is assigned to each symbol.

d. Optimum symbol size. How large (bright, etc.) does the selected symbol have to be in order to provide good legibility under the range of operational conditions to be encountered? Keep the symbol as small as practical in order not to interfere with the readout of other information, but large enough to ensure accurate transmission of the required information. This consideration includes the visual angle subtended by the symbol as well as the stroke-width-to-height ratio of each symbol.

e. Spacing of symbols. What spacing requirements need to be considered to present the maximum amount of required information on the display surface? The formatting of the symbology is important to produce the least amount of interference.

f. Ease of learning. Can the user population readily learn the alphabet selected and not show a performance deterioration during adverse or emergency situations?

g. Safety factors. Is there a provision for a safety factor (an alphabet of less than the maximum amount of symbols) in the event that the code will have to be used in noise or less than ideal conditions? If the minimum amount of discriminability is left between symbols in an alphabet, the introduction of relatively low amounts of noise will, in most cases, significantly reduce performance.

h. Technical feasibility. Is presenting the alphabet feasible with the equipment with which it is to be used? The more detailed and complex the alphabet is, the more sophisticated the generation equipment must be to present it with the desired resolution.

8.4 Coding Categories

Codes may be divided into the following categories:

(1) Single coding

4 = 400 knots

(2) Redundant coding

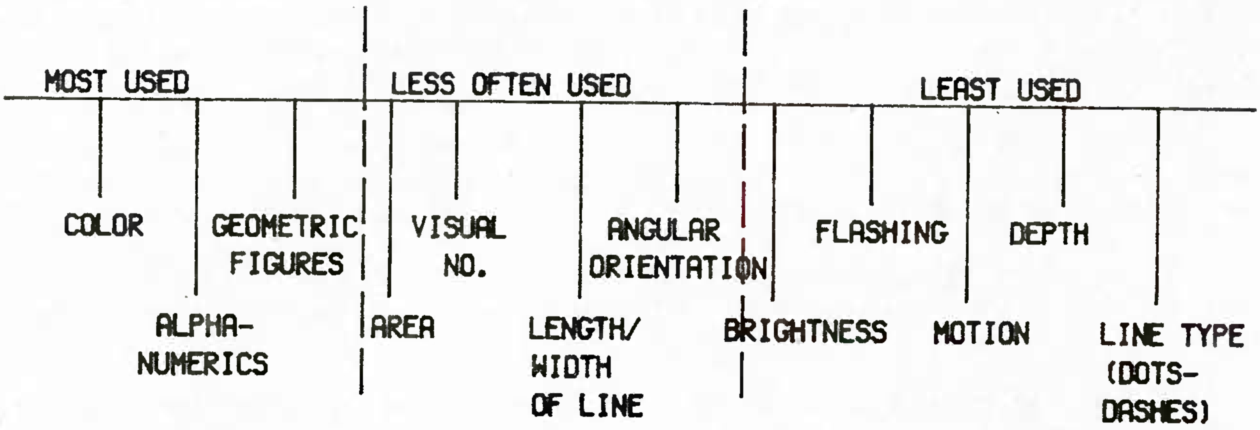
$\boxed{4}$ = 400 knots (both numeral and square indicate 400 knots)

(3) Compound coding

= 400 knots (numeral means 400 knots; triangle means jet powered aircraft).

8.5 Advantages and Disadvantages of Available Codes

Figure 195 indicates the most and least used codes. At any given time the observer is capable of identifying about 7 ±2 alternatives along a single coding dimension. As the number of alternatives increases, speed and accuracy decrease in a linear manner (Howell et al., 1966).



Note. Does not imply a scale of desirability, only frequency of use.

Figure 195. Most and least used codes.

8.6 When Coding Should Be Used

8.6.1 How Many Data Points Must the Display Have Before Coding Is Necessary?

Factors to be considered are:

a. Density. Number of characters/data points in display (100 or more).

b. Complexity. Percent of characters irrelevant to observer's task. (The designer may not be able to define complexity in detail in advance of design. Where it is suspected, however, that as many as 10 percent of display characters may have to be disregarded by the observer, coding should be employed.)

c. Speed of updating. The faster displayed information must be updated, the more coding of that information is required. However, quantitative information on speed requirements is not available.

As density and complexity increase, observer accuracy is reduced and coding becomes important. Figure 196 illustrates accuracy in updating information. Figure 197 illustrates percent of observational cycles (trials) in error when counting characters. Note that these graphs and others in this section represent data gathered under relatively ideal laboratory conditions. Figure 198 shows how correct identification of alphanumerics decreases as complexity increases (percent of task irrelevant characters) (Dyer & Christman, 1965).

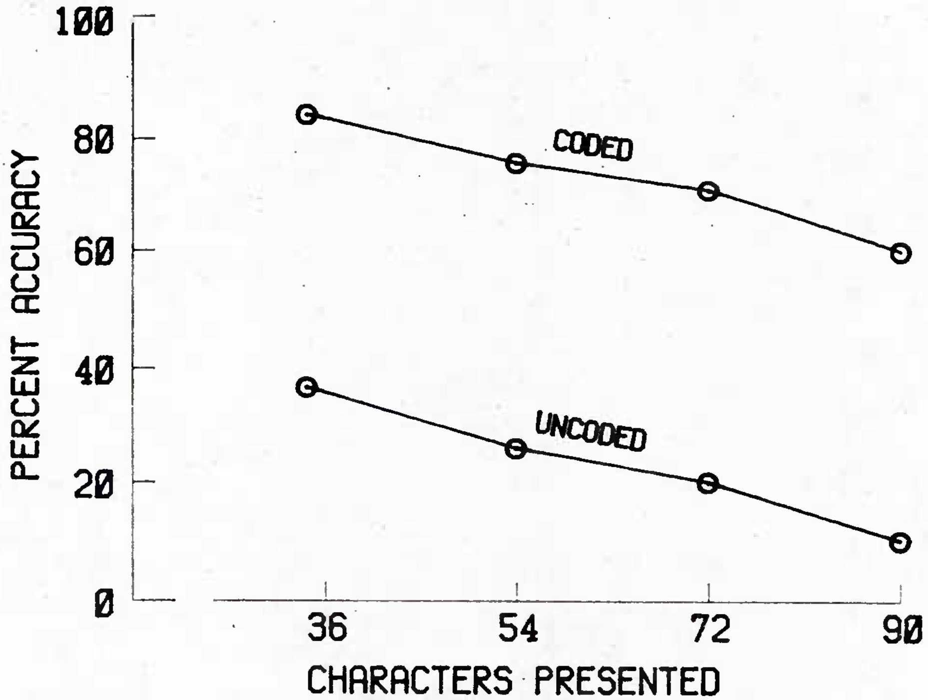


Figure 196. Accuracy of updating displayed information as a function of density (Hammer and Ringel, 1966).

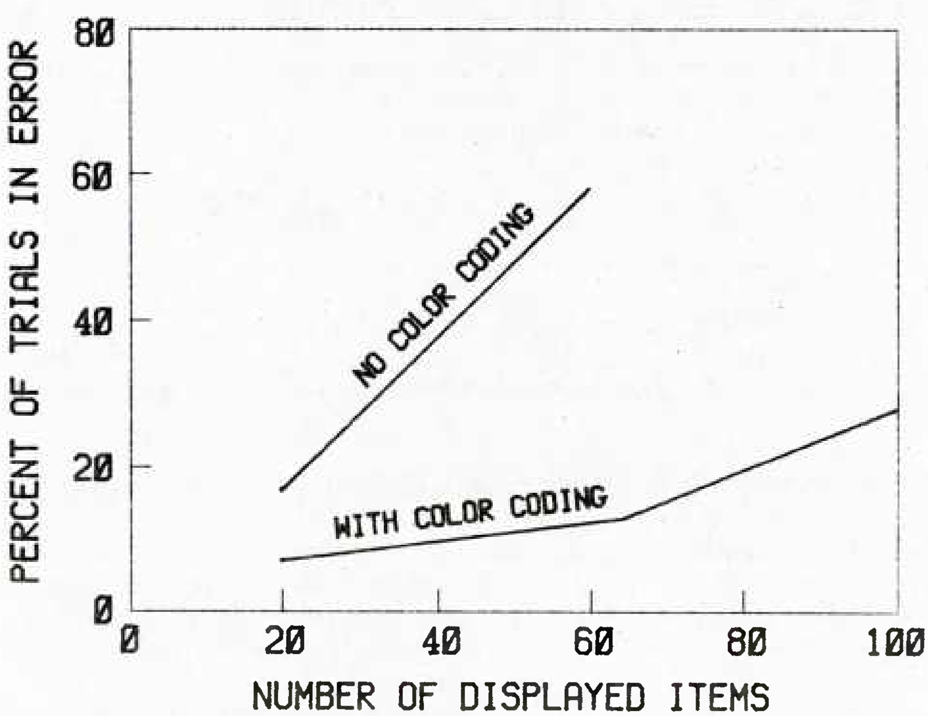


Figure 197. Counting errors as a function of display density with and without color coding (Smith, S. L., 1963b).

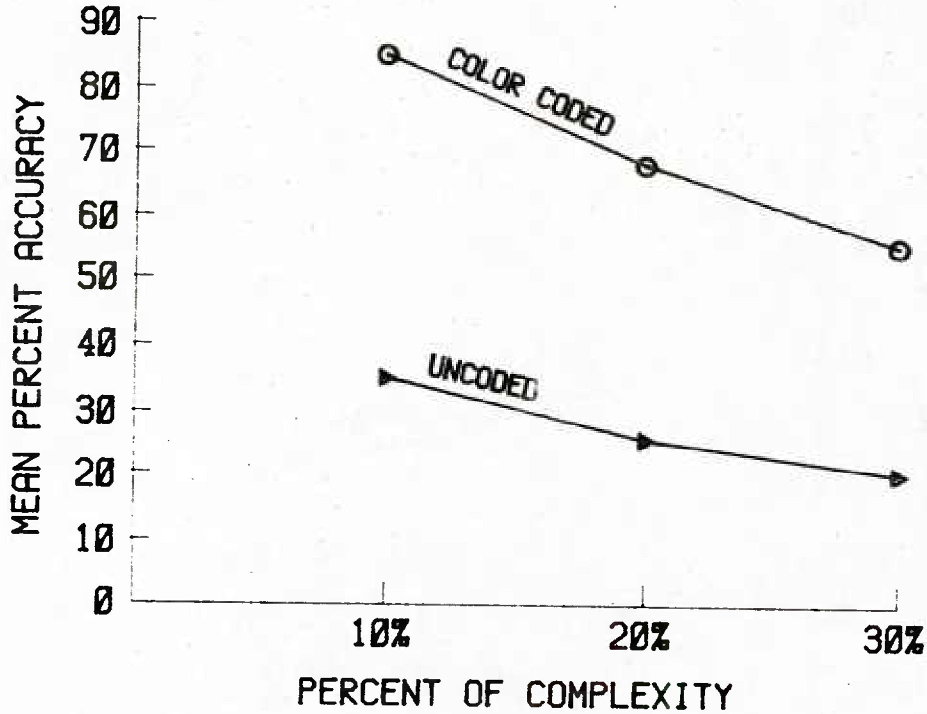


Figure 198. The effect of complexity on accuracy (Dyer & Christman, 1965).

8.6.2 How Short Must Display Exposure Time Be Before Coding is Necessary?

As display exposure time is reduced, observer accuracy decreases correspondingly. Figure 199 demonstrates that the curve of correct observer performance is almost a perfect negative linear relationship with exposure time.

8.6.3 What Type of Coding Is Best for Particular Applications?

The designer must consider:

a. Code type (e.g., color, shape, alphanumeric).

b. Code characteristic (e.g., if color, which color; if geometric figure, which figure?).

c. Observer's task (locating, counting, identifying, updating).

Available information is incomplete. Comparisons have been made between color and three shape codes (military symbols, geometric forms, and aircraft shapes) for counting. The codes used in this study (Wolf & Zigler, 1959) are shown in Figure 200. Average counting time for these codes is shown in Figure 201 and percent of trials in error is shown in Figure 202. Color is superior at all density levels even to the best of the shape codes. This applies of course, only to counting or searching for characters.

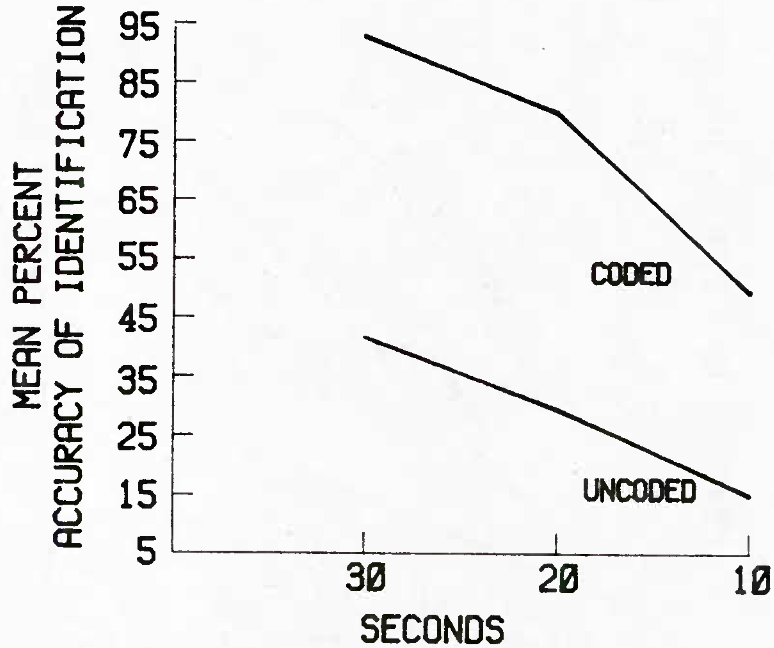


Figure 199. The effect of display exposure time on accuracy of identification (Smith, S. L., 1963a).

COLOR (MUNSELL NOTATION)	MILITARY SYMBOLS	GEOMETRIC FORMS	AIRCRAFT SHAPES
GREEN (2.5G 5/8)	RADAR	TRIANGLE	C-54
BLUE (5BG 4/5)	GUN	DIAMOND	C-47
WHITE (5Y 8/4)	AIRCRAFT	SEMICIRCLE	F-100
RED (5R 4/9)	MISSILE	CIRCLE	F-102
YELLOW (10YR 6/10)	SHIP	STAR	B-52

Figure 200. Codes used in code comparison study.

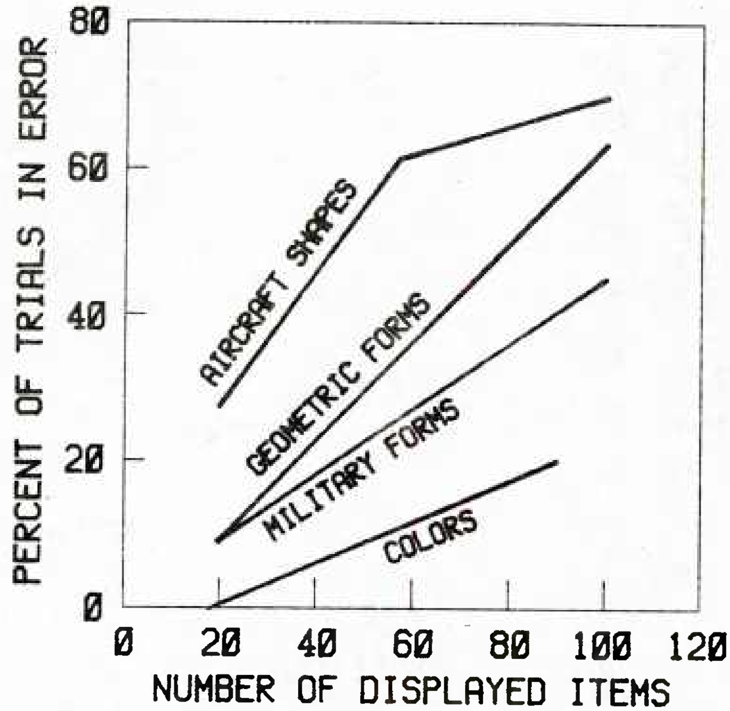


Figure 201. Counting errors as a function of display density, comparing color coding with the three shape codes (Wolf & Zigler, 1959).

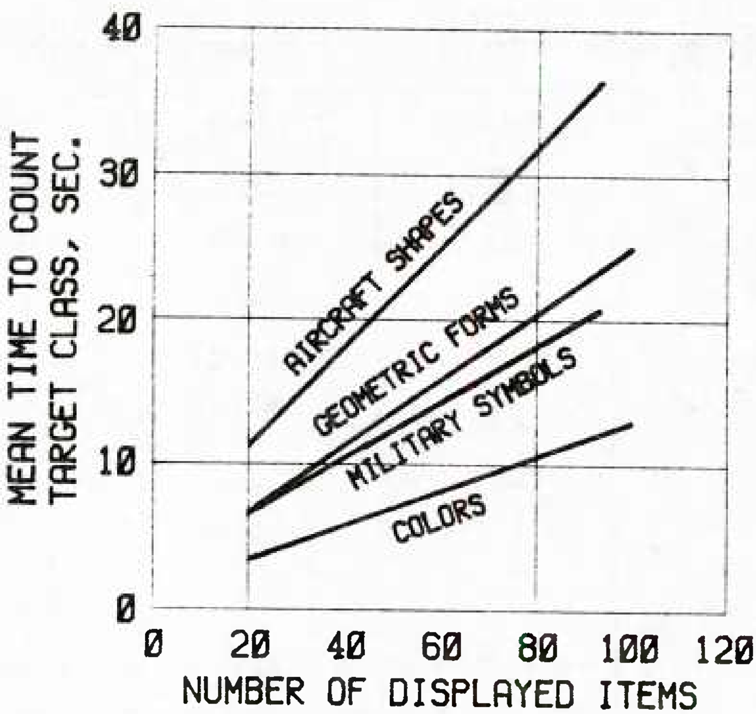


Figure 202. Average counting time as a function of display density, comparing color coding with the three shape codes (Wolfe & Zigler, 1959).

Recommended practice:

a. Use alphanumerics when identification is most important.
b. Use color when searching or locating is most important.
c. Use symbols/shapes when qualitative objects are represented.

8.7 Individual vs. Group Displays

There is some evidence that individual displays are slightly superior to group displays when updating uncoded displays. However, this difference becomes insignificant when displays are coded (Figure 203).

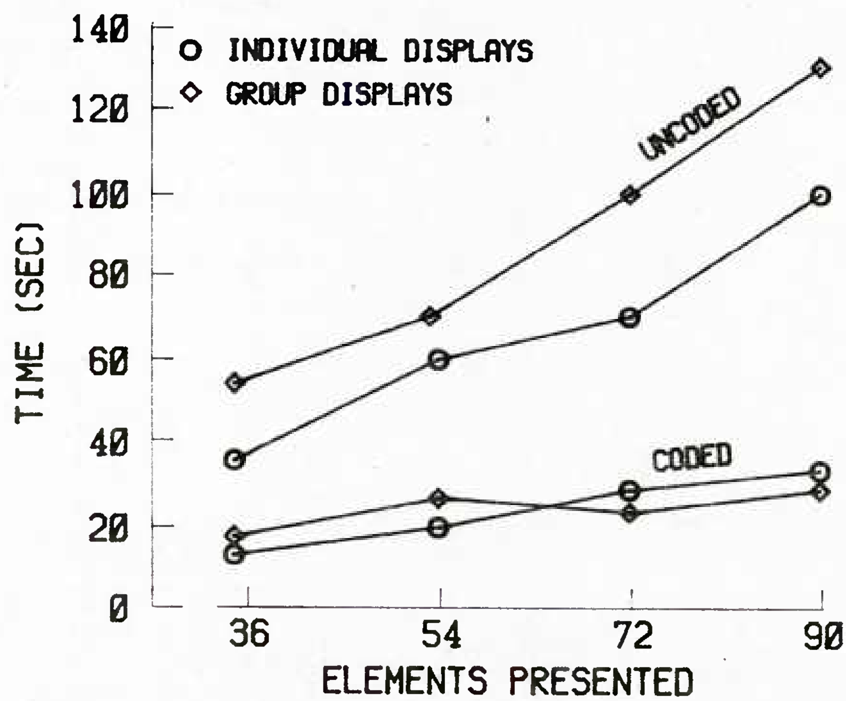


Figure 203. Mean time for coded and uncoded charts at each level of elements presented (Alluisi & Martin, 1958).

8.8 Should Single, Redundant, or Compound Coding Be Used?

There is some evidence (Alluisi & Muller, 1956) that redundant coding is slightly more effective than single coding.

8.9 How Many Coding Levels Should Be Employed?

a. Coding level. Values within each code type (e.g., color) which are equally identifiable (e.g., red, yellow, green).

b. General rule. Use as few coding levels as necessary. Code steps in Table 45 are maximum values under laboratory conditions. For operational use, it is desirable to halve these values. The effect of increasing code levels on operator performance is to reduce observer accuracy (see Figure 204).

Table 45

Advantages and Disadvantages of Available Codes

Code	Maximum No. Code Steps[a]	Evaluation	Advantages/Disadvantages
Color	Slides - 5-7 CRT - 3-5 Paint - 7-11	Good	Little space required. Objects easily identified, low training requirement.
Alphanumerics	Unlimited combinations	Good	Little space required if good contrast and resolution. Longer identification time than color.
Shape (geometric figures)	10-100 pictorial	Good	Little space required if good resolution.
Area/size	3	Fair	Requires considerable display space.
Length/width of line	4-5	Fair	Clutters display.
Visual No.	6	Fair	Requires considerable display space.
Angular orientation	8	Fair	95% of estimates will be in error by less than 15 degrees.
Brightness	3-4	Poor	Poor contrast reduces visibility. Difficult to distinguish between any two brightness ratios.
Flash rate	3	Poor	Distracting and fatiguing. Difficult to distinguish between more than two flash rates unless the rates are very different. Extremely useful as an alerting or warning signal.

[a]Generally will give overall accuracies of 95% or better. All figures given are for laboratory conditions. For operational displays, it is better to be conservative (Baker & Grether, 1954).

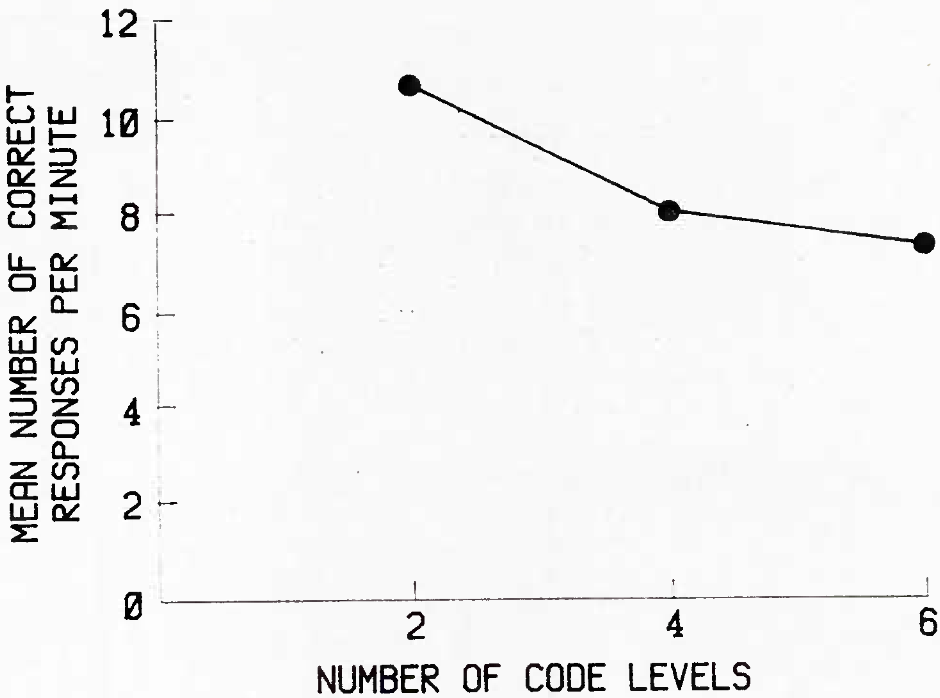


Figure 204. Effect of number of code levels on observer performance (Anderson & Fitts, 1958).

8.10 How Much Improvement in Observer Performance Can One Expect with Coding

Table 46 indicates that coding produces marked improvement in observer performance. Since the situation and the task both determine the amount of improvement (improvement can vary from negligible to great), Table 46 should be used with caution in making quantative predictions.

Table 46

Improvement in Observer Performance When Displays are Coded

Original Displays	Code Type	Observer Function	% Accuracy Improvement	% Response Time Improvement
Alphanumerics	Color	Locating	44	—
Alphanumerics	Color	Counting	86	72
Alphanumerics	Size	Update	50	65
Map	Conspicuity (border)	Information Assimilation & Extraction	97 & 57	—
Alphanumeric and Shape	Color	Search & Count	15 53	5-25
Alphanumeric	Size	Update	49	—

8.11 Additional Factors to Be Considered

Which codes to use and how depends in part on display parameters discussed in earlier sections. Any parameter that reduces display visibility increases display difficulty level and the need for coding. The following factors are especially important.

a. Display brightness/resolution/contrast. If display brightness or resolution is expected to be significantly less than levels recommended earlier, alphanumeric coding is preferable to color or shape (geometric figure) coding. If alphanumeric coding cannot be used, then shape coding is preferable.

For the display of color coded points or small symbols, an empirical spacing of at least three lines is required to prevent color fusing (Wolf Research and Development, 1968).

The optimum range for display contrast when a seven-color display is being used is from 20 to 30:1. However, acceptable levels of performance have been recorded as low as 10:1 for an additive color display (Rizy, 1967).

b. Display formatting. In formatted displays, characters are distributed by rows, columns, or quadrants; in unformatted displays, characters are distributed randomly. Coding is more likely to be required in unformatted displays.

The following sections present detailed information on each of the major code types.

8.12 Alphanumeric Coding

Alphanumeric coding is particularly useful when the observer's task is largely identification of a character set. Outside of the particular advantage color codes have for locating the desired character set (shorter search time) (Barmack, 1966), alphanumerics are about as effective as color codes (see Table 47). In addition, they are much less expensive and technically less difficult to display than color codes.

Unlike other forms of display coding (where levels within the code category are highly restricted), there is no practical upper limit to the number of alphanumeric combinations that can be used by the designers. Search time, however, increases with an increased number of alphanumerics.

The best use of letters and numbers is in short code words for items that represent one of a kind (e.g., three-letter code names for cities).

8.13 Shape (Geometric Figures) Coding

Shape coding should be used when color is not feasible or too expensive, and particularly to represent qualitative objects.

Select shapes or symbols that are associated with the real objects they represent (e.g., airplanes for aircraft, ships for ships). Symbols that are used should be simple and symmetrical, have a continuous contour, enclose a relatively large area, be familiar to observers, have a sharp angle or simple curves. The symbols shown in Figure 205 have been found to be identified 100 percent of the time if their maximum dimension subtends a visual angle of 10 minutes of arc and if contrast and definition are near optimal. These symbols are for slide projected displays only.

Table 47

Effect of Coding Methods on Operator Tasks

Tasks	Rank Order of Code Categories (See Figure 201)				
	1	2	3	4	5
Identify	Numeral 13.64[a]	Letter 13.02	Shape 12.53	Color 12.34	Configuration 11.77
Locate	Color 8.46	Numeral 7.42	Letter 7.25	Shape 6.94	Configuration 4.03
Count	Numeral 12.60	Color 12.22	Shape 11.49	Letter 11.11	Configuration 7.07
Compare	Numeral 6.85	Color 6.72	Shape 6.56	Letter 6.33	Configuration 4.76
Verify	Numeral 10.01	Color 9.95	Shape 9.50	Letter 9.05	Configuration 6.60

[a]All scores reported in terms of mean correct responses per minute.

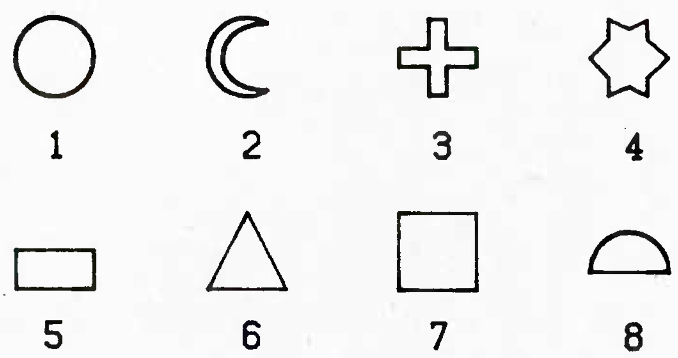


Figure 205. Common geometric symbols.

Table 48, taken from Semple et al., (1971) presents the results of a series of studies on shape that could most easily be discriminated.

Ten different symbols are a good upper limit; however, the fewer shapes used, the more easily they are recognized. Under adverse display conditions, no more than six should be used.

Table 48

Ranking of Forms for Studies Reviewed

	Study	Triangle	Square	Circle	Rectangle	Hexagon	Star	Other Cross	Parallelogram
1.	Kleitman & Blier (1928)	1[a]	3	2	-	-	4	-	-
2.	Collier (1931)	1	2	4	-	5	-	-	3
3.	Munn & Geil (1931)	1	2	3	4	5	-	-	-
4.	Helson & Fehrer (1932)	1	3	4	2	-	-	-	-
5.	Whitmer (1933)	1	3	5	4	6	-	2	-
6.	King et al. (1944)	1	2	3	-	-	-	-	-
7.	Hochberg et al. (1948)	-	2	1	-	-	-	3	-
8.	Hanes (1950)	1	2	3	-	-	-	-	-
9.	Fehrer (1935)	-	3	1	-	2	-	-	-
10.	Kofka (1935)	-	-	1	-	-	-	-	-

[a]1 = most discriminable;
2 = second most discriminable, etc.

The circle, rectangle, cross, and triangle are the most distinctive common geometric forms. Squares, polygons, and ellipses should be avoided. Variations of a single geometric form, such as sets of round, pointed, and triangular characters, should be avoided (Human Engineering Laboratory, 1965) (see also Table 49).

Table 49

Minimum Satisfactory Sizes for Visual Symbols used on CRT Displays
(Human Engineering Laboratory, 1965)

Symbol	Description	Dimension (inches)
Spots and circles	Diameter	.02 inch
Squares Rectangles	Length of Short Side	.02 inch
Lines	Width	.005 inch (for bright line on dark background) .01 inch (for dark line on bright background.

8.14 Other Codes

Other codes are not recommended unless color, alphanumeric, and shape codes are not feasible. The available information concerning these codes is as follows.

8.14.1 Size Coding

Size coding is infrequently used. A safe upper limit on number of sizes is 3. Beyond that number, errors become unacceptable. Steps coded in logarithmic area progression are more easily discriminated than steps coded in linear area progression (Baker & Grether, 1954) (see Figure 206).

Size can also be used in combination with alphanumerics. That is, in matrix type alphanumeric displays, a larger type face can be used to emphasize particular characters or items of information (Hammer & Ringel, 1966) (see Figure 207).

When size is used in this way, the mean time to locate coded updated information is 65 percent less than for uncoded updates and errors of omission are reduced by 50 percent. As the number of characters is increased from 36 to 90, the mean time to locate coded updates is increased 100 percent, but that of uncoded updates is increased 150 percent.

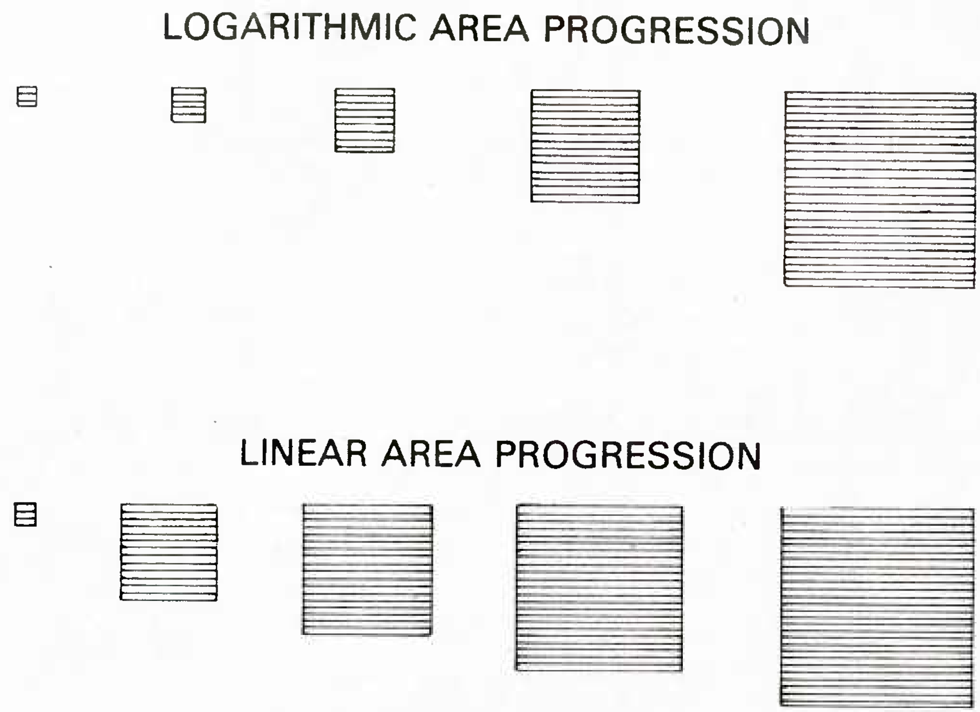


Figure 206. Steps coded in logarithmic progression are more easily discriminable than steps coded in linear progression.

FRIENDLY TACTICAL UNIT STATUS

UNIT	ACTIVITY	EFF STRENGTH	TERRAIN	ARMOR STATUS	WEATHER
23	LANDING	77	FARMLAND	92	DAMP
72	REBUILDING	96	LOWLAND	85	ATTACKING
57	ASSEMBLING	87	RIVERS	91	SNOW
82	WITHDRAWING	78	JUNGLE	82	HUMID
53	ASSAULTING	80	MARSHLAND	76	RAIN

Figure 207. Example of size coding updated alphanumeric information.

8.14.2 Flash Rate Coding

Flash rate coding has been used primarily as an attention-getting device and should be reserved for emergency situations only.

Using several levels of flash rate information results in poor observer performance (Newman & Davis, 1962). Three flash rates should be the limit in any practical situation. These rates are: 1.0, 2.5, and 5.0 per second assuming a 50 percent on-off ratio.

After reviewing the available literature, Semple et al. (1971) concluded that:

a. Flash rate coding is the least desirable of the several dimensions of coding available for visual displays. As such, it should be incorporated into the display only as a "last resort."

b. Flash rate coding is useful as an attention-gaining device, but limited in scope, with three to five distinct, discriminable flash rates available. In this category, Gerathewohl (1954) suggests flash rates of 1, 2, and 4 flashes per second with durations of 1/2, 1/4, and 1/8 second each.

8.14.3 Brightness Coding

Brightness coding is most effective when limited to two steps (dim and bright). It is not ordinarily recommended because (1) observer cannot reliably discriminate more than two levels and (2) ambient illumination may "wash out" the brightness display.

8.14.4 Special Codes

In radar-type displays, when the information to be displayed is bearing, angular orientation has been employed. With this coding, 50 percent of the course estimates were in error by less than 15 degrees.

Inclinations of 0, 90, 180, and 270 degrees can be identified accurately. Inclinations of 45, 135, 225, and 315 degrees may be used if more bearing information must be displayed. Line length should be between .2 and .3 inch (Human Engineering Laboratory, 1965) (Figure 208).

Angular orientation coding may also be used with banks of identical indicators in which direction of the pointer for normal operation has been standardized. Deviations from this normal direction indicates an abnormal condition. Minimum deviation of 45 degrees from normal orientation is required for high probability of detection with 90 degrees preferred (see Figure 209).

Location coding may be accomplished by color coding different locations or by outlines around each unique displayed object or group of displays. An intensive border has also been used particularly with map displays (Hammer & Ringel, 1966).

This type of coding improved observer performance 97 percent over unaided performance when response time was limited; 57 percent, when response time was unlimited.

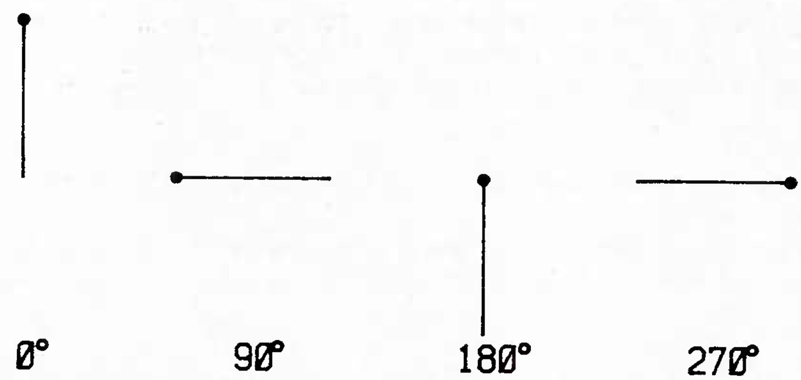


Figure 208. Inclination coding.

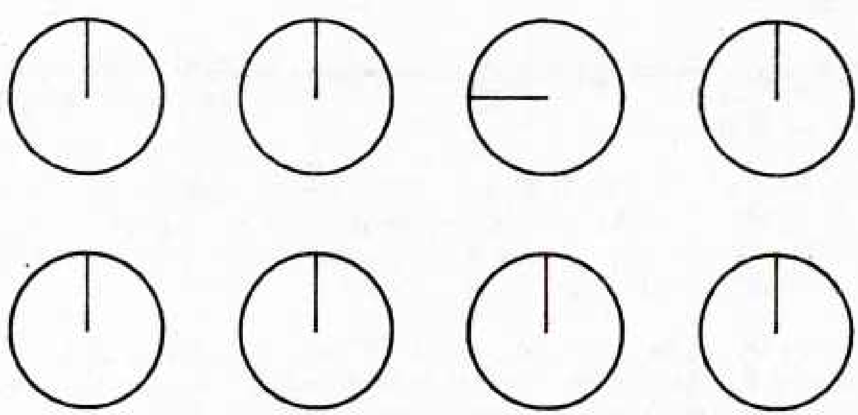


Figure 209. Angular orientation used with indicators (Alluisi, 1961).

8.14.5 Coding Combinations

No more than two codes should be combined when rapid, accurate reading of the display is required. Potential combinations of coding techniques (compound coding) are summarized in Table 50.

Table 50

Summary of Potential Combinations of Coding Techniques

	Color	Numeral & Letter	Shape	Size	Brightness	Location	Flash Rate	Line Length	Angular Orientation	Stereoscopic Depth	Pattern & Configuration
Color	-	X	X	X	X	X	X	X	X	X	X
Numeral and Letter	X	-	-	X	-	X	X	-	-	-	-
Shape	X	-	-	X	X	-	X	-	-	-	X
Size	X	X	X	-	X	-	X	-	-	-	X
Brightness	X	-	X	X	-	-	-	-	-	-	-
Location	X	X	-	-	-	-	-	-	X	-	-
Flash rate	X	X	X	X	-	-	-	-	-	-	X
Line length	X	-	-	-	-	-	-	-	X	-	-
Angular orientation	X	-	-	-	-	X	X	-	-	-	-
Stereoscopic depth	X	-	-	-	-	-	-	-	-	-	-
Pattern and configuration	X	-	X	X	-	-	X	-	-	-	-

8.15 Color Coding

Much of this material is taken from Krebs, Wolf, and Sandvig (1978).

8.15.1 Steps in Designing an Electronic Color Display Format

The value of color as a coding method is entirely dependent on its effective use in a specific application. That is, it can be beneficial, neutral, or distracting. Which of these outcomes will occur is a function of how, where, and when it is used. The operator task, the environment, the display medium, and the specific way in which color coding is applied are all important. Table 51 shows the maximum and minimum gain or loss (in percent change) in using color relative to the indicated achromatic coding dimensions.

a. Determine the colors available with the display system hardware.

b. Determine the maximum luminance achievable with each color.

c. Consider the ambient illumination in which the display will be used:

(1) Dark.
(2) Average room luminance.
(3) Variable, dark to bright sunlight.

d. Calculate the luminance contrast achievable for each color under the worst possible operating conditions (i.e., high ambient light, such as bright sunlight shining on the display surface). Any color that will not provide adequate contrast under "worst case" conditions should not be used as a primary (nonredundant) information source. It should be used elsewhere with caution.

e. Of the remaining colors available, select up to five (maximum). The particular colors chosen should be widely spaced in wavelength from one another.

f. Determine where the display will most likely be located relative to the operator's normal viewing position.

(1) If the display is to be peripheral to the line of sight, any signal drawing attention to it should be white if the signal is also peripheral. If colored (blue), the signal should be placed in the line of sight.

(2) If the display is within the operator's normal scan pattern, it can be considered foveal. Caution should be taken to determine if this is a correct assumption.

g. The following size constraints should be observed:

(1) On the display itself, all colored alphanumerics and symbols should be at least 21 minutes of arc high. Lines should be about 3 to 4 minutes of arc wide for any graphics.

(2) Avoid the use of blue in the coding of alphanumerics or any small symbols.

h. Consider the use of color on the display:

(1) When symbols are difficult to see, as when they are superimposed on imagery, use color as a redundant dimension to improve symbol visibility.

Table 51

Range of Percent Difference Scores for the Use of Color (Christ & Teichner, 1974)

	Identification Task			Search Task		
	Minimum	Maximum	n[a]	Minimum	Maximum	n
Unidimensional						
Brightness	+29	+32	2	+43	+43	1
Size	-6	+111	6	+40	+40	1
Geometric shape	-38	+33	11	+6	+42	5
Other shapes	0	+118	6	+30	+63	2
Letters	-29	-15	6	+10	+7	2
Digits	-48	+26	17	-3	+42	4
Multidimensional						
Size	-10	+176	7	—	—	0
Geometric shape	-28	+202	15	+50	+53	3
Other shapes	-2	+62	12	+41	+69	6
Letters	+4	+46	4	—	—	0
Digits	-51	+29	5	—	—	0
Interference						
Size	-29	0	14	—	—	0
Geometric shape	-42	+1	4	-8	-8	1
Other shapes	-43	-17	4	-10	-3	2
Digits	-14	+2	7	—	—	0
Complete Redundancy						
Size	+22	+60	3	+32	+32	1
Brightness	+24	+104	2	+32	+32	1
Geometric shape	—	—	0	+21	+32	2
Letters	—	—	0	+53	+63	2
Digits	+2	+2	1	+60	+74	3
Partial Redundancy						
Digits	—	—	0	-23	-73	20
Maps	+1	+1	1	—	—	0
Static-ground photo	+29	+29	1	+32	+47	1
Static-aerial photo	+2	+2	1	+17	+17	1
Dynamic-aerial film	+3	+3	1	—	—	0
Dynamic-aerial TV	+3	+3	1	-3	-3	1

[a]Number of comparisons in literature.

(2) As a general rule, use red, green, and yellow according to the conventional meanings only (i.e., red = danger, yellow = caution, green = safe).

(3) For data displays, use red, yellow, or green alphanumerics as a partially redundant code to indicate the present relative status of the numbers presented. For example, a digital representation of steam pressure or radiation might be coded as red if it is too high, yellow if it is borderline, and green if it is within tolerance.

(4) Use color to group spatially separated, but related, information (e.g., a series of checkpoints on a map or friendly vs. enemy installations).

(5) Use color to reduce the effective density of items on a cluttered display by separating them into several color categories where the symbols can be assigned to task-related groups.

i. Consider the other displays the operator will be using in conjunction with this display. If any of them are color displays, observe the following:

(1) Similar colors should have the same or similar meanings across the display set. They should never have contradictory meanings.

(2) Color can be used to visually group information across displays as well as within one display.

j. Consider the operator's workload during the display use. The higher the workload is, the more important is the clarity of the displayed information. Under high workload conditions:

(1) Use fewer than the maximum number of colors. The more complex the color code, the more difficult it will be to use.

(2) Use color primarily as a fully or partially redundant dimension (i.e., to enhance symbol visibility or to convey relative information quickly).

(3) Avoid the use of irrelevant color (i.e., a multicolored display where color has no specific, necessary, or useful task-related meaning).

8.15.2 Physical Specifications for Color Symbols

8.15.2.1 Symbol Size and Resolution Requirements. An important distinction must be kept in mind when specifying symbol sizes for color displays. The difference between seeking a symbol and perceiving its color leads to different requirements. That is, a symbol may be seen and even identified, but not be large enough for its color to be recognized. In the following paragraphs, size requirements are given for color perception unless otherwise specified. Requirements will also vary with symbol luminance and contrast and will be affected by the range of expected variations in ambient illumination.

Color symbol size requirements for CRT displays include:

a. Alphanumerics--21 minutes of arc minimum height.

b. As the number of colors increases from 2 to 6, minimum height requirements increase up to about 45 minutes of arc (see Figure 210).

c. Symbol stroke width--2 minutes of arc minimum.

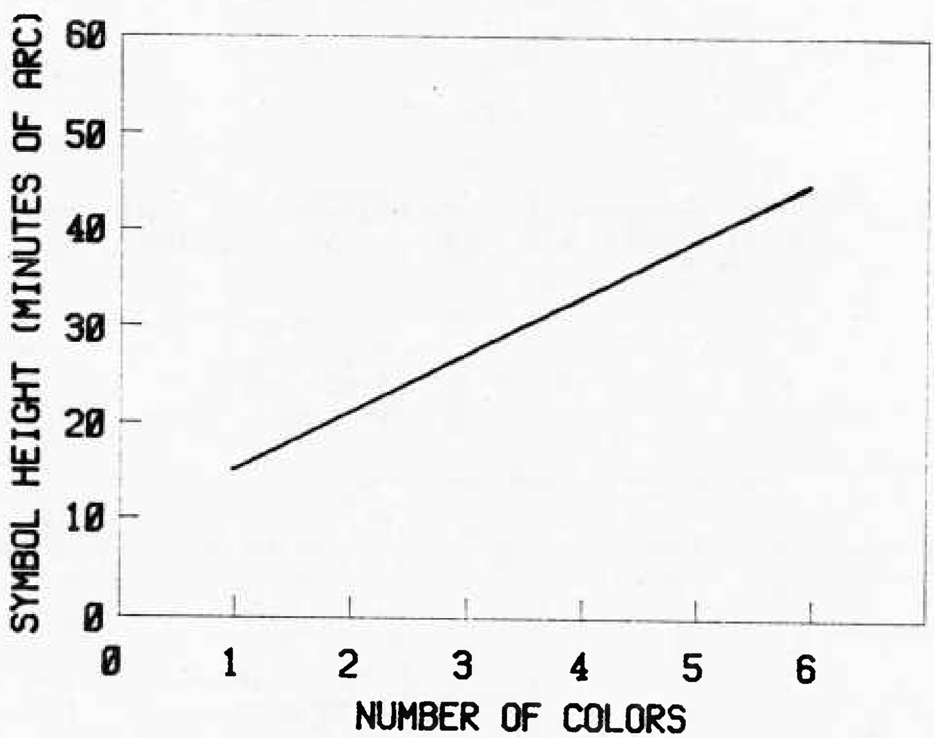


Figure 210. Recommended symbol size as a function of number of colors used on the display. (Below 21 minutes of arc, color perception may be adversely affected.)

d. Line width for graphics--4 minutes of arc minimum.

e. Symbol aspect ratio--5:7 or 2:3 width/height.

8.15.2.2 Symbol Size. As shown in Figure 210, minimum symbol size required for adequate color perception varies from about 21 to 45 minutes of arc, depending on the number of colors used (Haeusing, 1976; Bishop & Crook, 1961). If luminance contrast is low or the display is degraded by noise and/or poor resolution, symbol size should be increased beyond the minimum recommended levels. The consequence of using smaller symbols may be either:

a. The symbol appears to be achromatic (white or grey), or
b. Two symbols of similar color may be confused (e.g., yellow and orange).

The latter point is the major reason for increasing symbol size as the number of different colors is increased.

8.15.2.3 Size vs. Symbol Luminance vs. Information Type. The particular information being displayed and the symbol luminance will also influence the recommended size of colored symbols. Table 52 (Smith, S. L., 1962) provides size recommendations for three classes of information at two levels of symbol luminance. Size range is expressed as the ratio of symbol size to viewing distance. For a given viewing distance, symbol height can be determined by multiplying this viewing distance by the appropriate table value. Note that, as signal luminance is decreased, symbol size must be increased. The type and "criticality" of the information also influences symbol size. The data in this table were calculated from achromatic data and have been adjusted to reflect the increased size requirements for color symbols.

Table 52

Recommended Minimum Alphanumeric Character Height for Colored Symbols on High and Low Luminance Displays

Type of Information Displayed	High Display Luminance (to 3.4 cd/m^2 (Min. of Arc)	Low Display Luminance (to 0.1 cd/m^2) (Min. of Arc)
Critical Data, Variable Position	(24) (38) .007 to .011	(38) (58) .011 to .017
Critical Data, Fixed Position	(17) (38) .005 to .011	(28) (58) .008 to .017
Noncritical Data	(10) (38) .003 to .011	(10) (38) .003 to .011

Note. Character height is expressed in minutes of arc and as a fraction of viewing distance.

8.15.2.4 Acuity As a Function of Color. The ability of the observer to discriminate fine detail varies as a function of both symbol color and background color. In Figure 211 (Meyers, 1967), reading accuracy is compared for four red and blue target-background combinations. The percentage of correct responses for the various-size openings in a Landolt ring (i.e., target detail) is plotted. The relative performance superiority obtained with red targets is clearly seen in this figure. The observer is more sensitive to fine detail at the red vs. the blue end of the spectrum.

Resolution requirements for matrix displays include:

a. Use larger dot format rather than smaller brighter dots (Ellis, Burrell, Wharf & Harokins, 1975).

b. A 5 x 7 dot matrix will provide marginal performance; larger matrix sizes should be used where possible.

For raster scan displays, use 15 scan lines per symbol height (minimum).

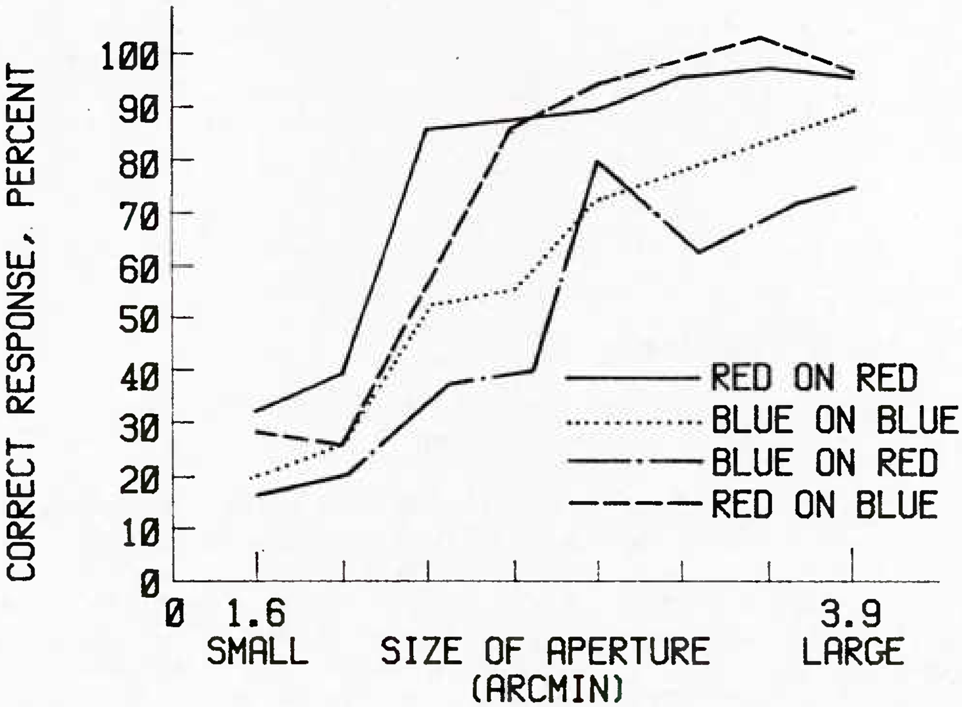


Figure 211. Acuity as a function of target and background color. (The target consisted of an opening in a Landolt ring. Aperture sizes varied from 1.6 to 3.9 minutes of arc.)

8.15.2.5 Resolution Requirements for Color Symbols. The display requirements for producing color symbols are closely related to color acuity. If the display is a raster scan CRT, the resolution is typically defined in lines per symbol height. If it is a matrix or LED display, the requirements are defined in terms of number of dots or strokes per character.

For raster displays, resolution is expressed as the minimum number of lines per symbol height. The standard for black and white TV systems is 10 lines per symbol height for 100 percent accuracy in character recognition (Shurtleff, 1966b). Since recommended symbol size for color symbols is about 50 percent greater than that for black and white symbols, a reasonable standard would be 13-15 lines per symbol height as a minimum.

8.15.3 Color Display Luminance and Contrast Requirements

The specification of required color symbol luminance depends on a number of factors. The most important of these are background luminance, ambient illumination, and symbol size. At very low symbol luminances or under very high ambient lighting conditions, the color of the symbol is also important. To specify luminances for a particular application, the entire range of ambient lighting conditions in which the display will be used must be specified.

Luminance and contrast requirements are:

a. Symbol luminance

(1) Minimum for good color perception—about 3 cd per m^2.

(2) Optimum under moderate lighting conditions--from 30 to 300 cd per m^2.

b. Background luminance

(1) Visibility of color symbols better on dark background.

c. Contrast

(1) For CRT displays, symbol-to-background luminance ratios of about 10:1 optimum.

d. Ambient illumination

(1) The higher the ambient illumination is, the higher the symbol luminance must be to achieve adequate contrast.

8.15.3.1 Contrast. Available data demonstrate that slightly better visibility of color displays is achieved if the symbols are displayed on a dark background. The reverse is true for black and white displays. This relationship is shown in Figure 212 (McLean, 1965) for performance on a dial reading task. Figure 213 compares performance between color and black and white symbols with equal luminance contrast. The relative superiority of color symbols (i.e., faster reading time) shown in Figure 213 is attributed to the additional benefits of color contrast. This advantage is only demonstrated for medium luminance contrast values. Beyond 15 percent contrast, color symbols were not significantly affected. Achromatic symbols were affected at both the lowest and highest values.

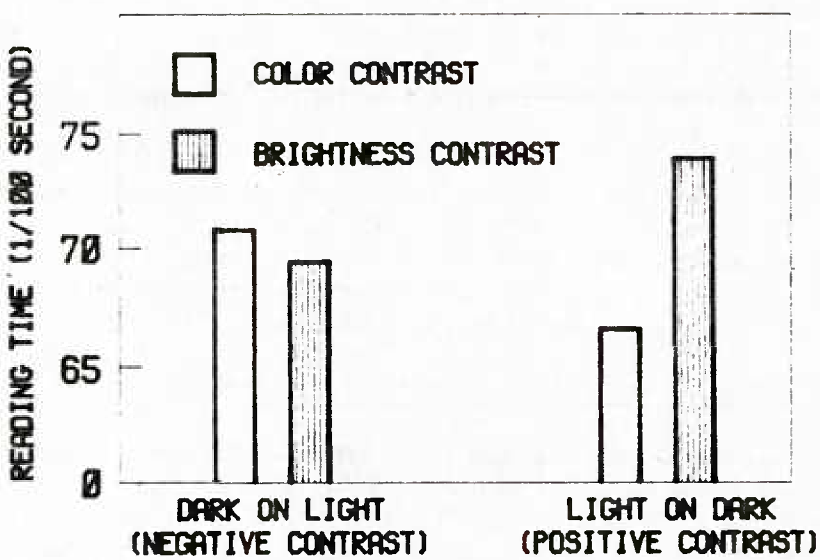


Figure 212. Effects of interaction between color brightness contrast with direction of contrast on reading time.

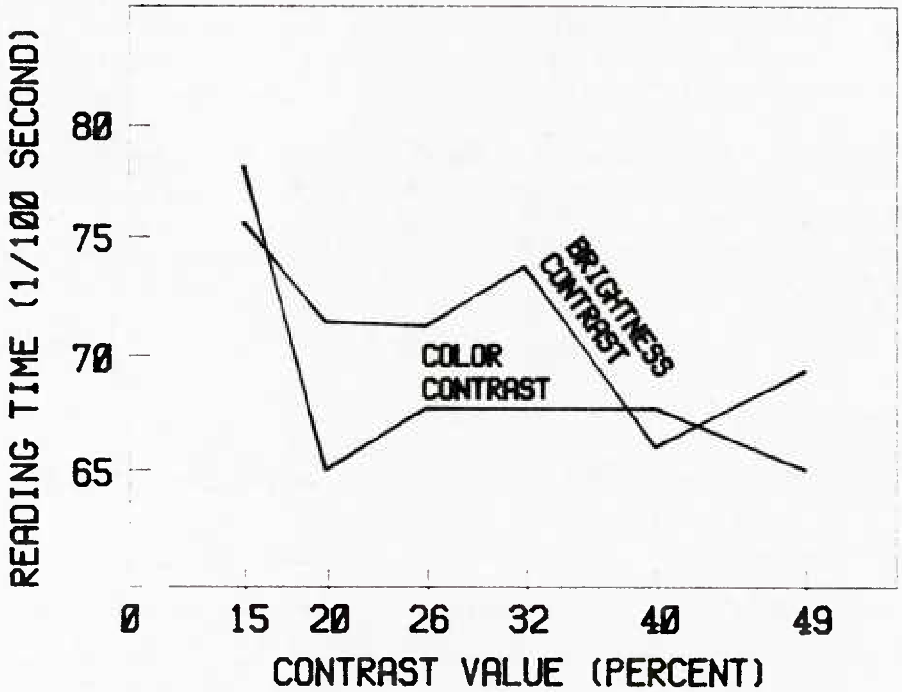


Figure 213. Effects of target-to-background contrast value on reading time.

Percent contrast is computed as follows:

$$\frac{L_B - L_T}{L_B} \times 100 \tag{8.1}$$

where L_B = background luminance and L_T = target luminance.

Haeusing (1976) recommends luminance ratios (L_1/L_2) of about 10:1 for multicolor CRT displays. Heglin (1973) recommends minimum luminance ratios of 5:1 or 8:1. The most relevant ratio would depend on other factors such as symbol size and number of colors used. If one factor is by necessity at a minimum value, values on the other factors should be adjusted to compensate. For example, if luminance ratios of 5:1 are likely, then symbol size should be increased well beyond 21 minutes of arc and/or the number of colors used should be reduced.

8.15.3.2 Ambient Illumination. For many real-world display applications, the major factor influencing display visibility is the ambient illumination. When external lighting can be maintained at a minimal level, achieving adequate visibility is relatively easy. When the ambient lighting is variable and/or becomes very bright at times, problems arise. The effect of adding environmental light to a display surface is to decrease the symbol-to-background contrast. Colors begin to desaturate or fade and, under very high ambient lighting, they may be completely washed out. Conversely, if outside lighting is very low, it may be desirable to keep symbol luminance at a minimum to maintain the operator's adaptation to the dark. If the symbols are colored, reduction of their luminance below about 3 cd per m^2 will seriously interfere with the perception of their color.

8.15.3.3 Low Ambient Illumination. Perception of surface colors on maps, charts, etc. requires luminance values of at least 3 cd per m^2. Below this minimum level, it becomes difficult to differentiate colors. Comfortable reading and good color perception require from 30 to 300 cd per m^2. At very high luminances (beyond about 3000 cd per m^2), surface colors become increasingly hard to see due to poor luminance contrast.

If the ambient lighting itself is colored (such as the red night lighting in some aircraft), surface colors of objects become more difficult to discriminate. They may markedly change in appearance. Table 53 (Semple et al., 1971) describes some of these changes. However, emissive color (CRTs, transilluminated displays) is not markedly affected by ambient lighting.

Table 53

Effect of Some Varieties of Colored Light on Some Colored Objects

Object Color	Red Light	Blue Light	Green Light	Yellow Light
White	Light pink	Very light blue	Very light green	Very light yellow
Black	Reddish black	Blue black	Greenish black	Orange black
Red	Brilliant red	Dark bluish red	Yellowish red	Bright red
Light blue	Reddish blue	Bright blue	Greenish blue	Light reddish blue
Dark blue	Dark reddish purple	Brilliant blue	Dark greenish blue	Light reddish purple
Green	Olive green	Green blue	Brilliant green	Yellow green
Yellow	Red orange	Light reddish brown	Light greenish yellow	Brilliant light orange
Brown	Brown red	Bluish brown	Dark olive brown	Brownish orange

When the display is to be used in light-restricted or night time conditions and the background is dark (below about 1 cd per m^2), required symbol luminance is lowest.

In Figure 214 (Pollack, 1968), observer response time data are given as a function of signal luminance and wavelength. Below about 0.1 cd per m^2, the symbols are seen as achromatic rather than colored signals. In these conditions, shorter wavelength signals in the blue to green region produce much faster response times than do the longest wavelengths toward the red end of the spectrum.

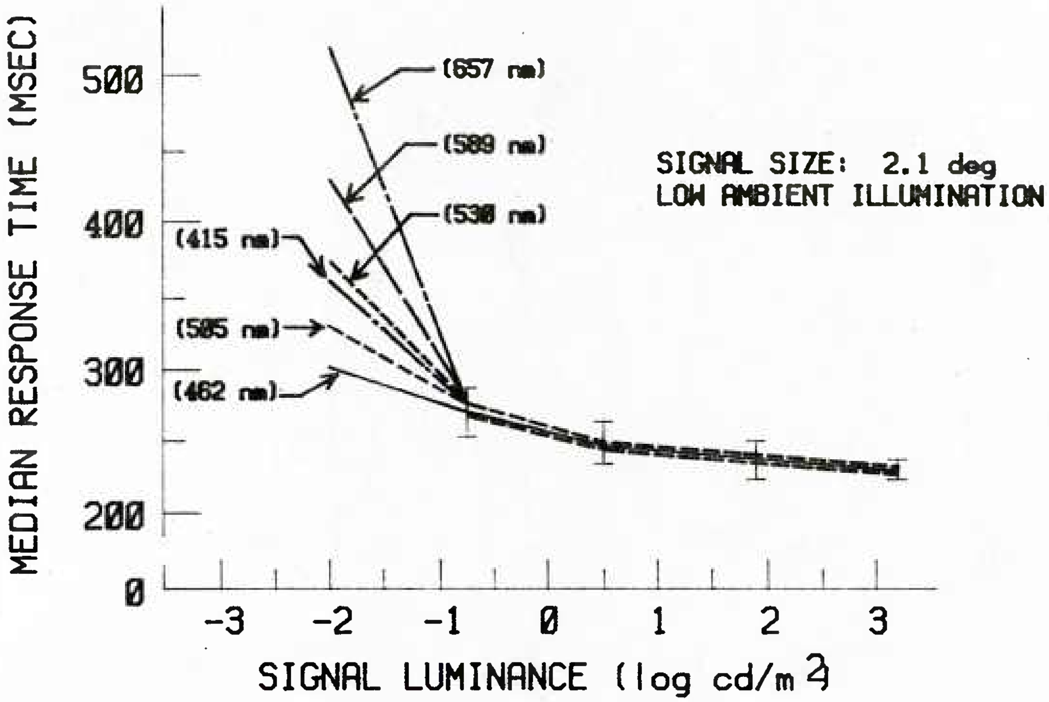


Figure 214. Median response time in milliseconds as a function of signal wavelength for five levels of symbol luminance (brackets indicate .01 confidence interval).

8.15.3.4 <u>High Ambient Illumination.</u> In general, the effect of ambient illumination striking the display surface is to reduce the symbol-to-background contrast. Under very high levels of ambient illumination, response time to signals at both the red and blue end of the spectrum are faster than those in the green-yellow to yellow-orange region. In Figure 215 (Tyte, Wharf, & Ellis, 1975) response time as a function of signal wavelength is shown at two signal luminances (A, high; B, low) under an ambient illumination of 10^5 lumens per m^2. The lower signal luminance produced a much greater effect (increased response time) in the yellow region. At 10^5 lumens per m^2, red symbols are more visible than green (Figure 216) symbols. To be equally visible in high ambient light, green signals should be about three times the luminance of the red.

In Figure 216 (Tyte et al., 1975), response time as a function of signal luminance is plotted for red, green, and yellow signals and the marked superiority of red under high ambient conditions is demonstrated.

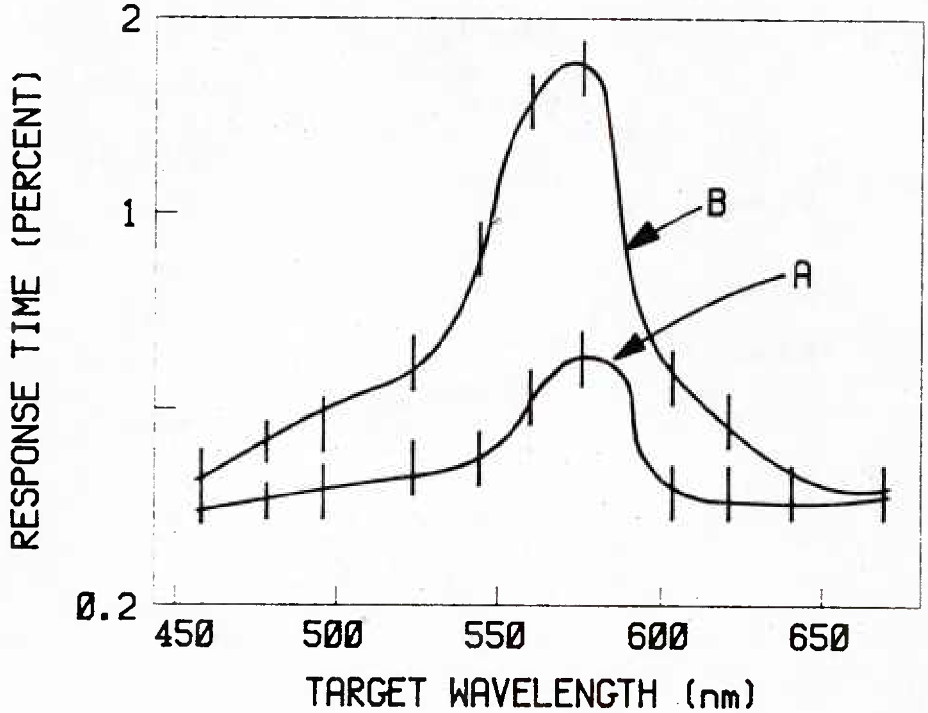


Figure 215. Response time as a function of wavelength.

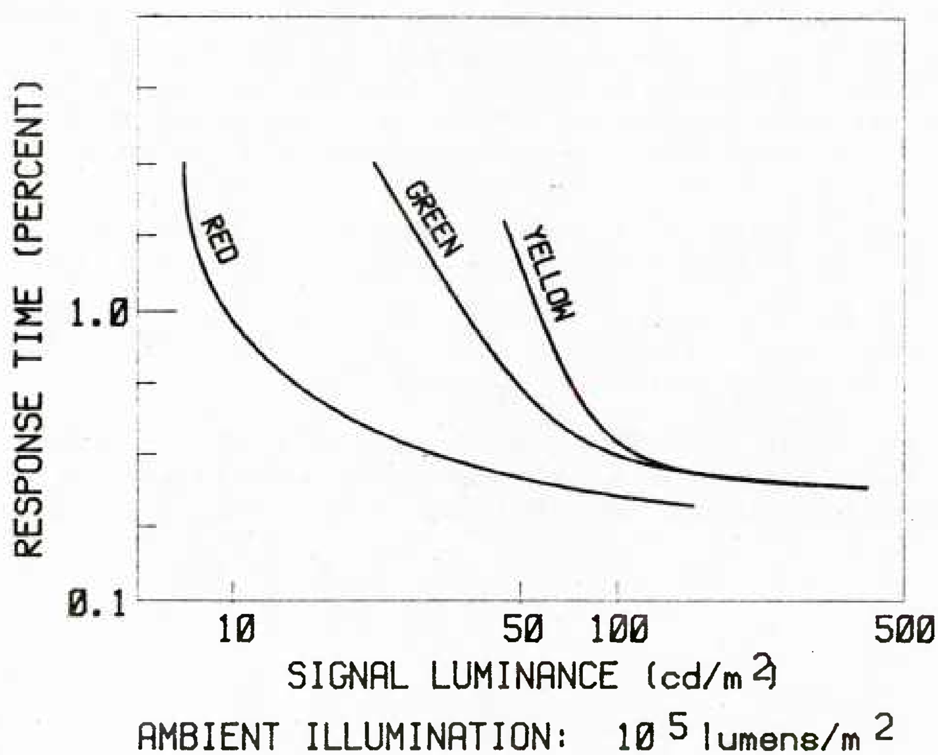


Figure 216. Response time as a function of signal luminance.

8.15.4 Display Location and Peripheral Vision

The eye is most sensitive to color within only a small part of the total field of view. Beyond this area, the eye is differentially sensitive to individual colors, both in terms of limits of field of view and in operator response time to different colors. (See Table 54 for a distinction between foveal and peripheral displays.)

Table 54

Criteria for Determining if a Display is Foveal or Peripheral

Display can be considered FOVEAL if:	Display must be considered PERIPHERAL if:
1. It is the only display the operator must see.	1. It is one of many displays
and	and
2. It is either very small—three or four degrees of visual angle.	2. It is outside of normal scan pattern.
or	or
3. It is actively and frequently scanned by operator	3. It is larger than three or four degrees of visual angle and portions of it are seldom scanned.
or	
4. It is one of several displays actively and frequently scanned by operator.	
or	
5. It is located in the operator's normal line of sight.	

8.15.4.1 Peripheral Sensitivity to Color. Of the various colors, the field of view is widest for yellow and narrowest for red and green. Within the total field of view, response time to different colored signals also varies. White has both the widest field of view and the shortest response times over the entire field, while red has both the narrowest field and the longest response times.

Blue, green, and yellow are roughly similar to each other and fall between the red and white plots. Therefore, a signal light should be placed as close as possible to the direct line of sight. White is the best choice for a signal light and red is the poorest in the periphery, as indicated by reaction times. The further into the periphery the light is moved, the greater is the discrepancy.

8.15.4.2 Peripheral Displays. If many displays are being used by the operator, some must by necessity be peripheral to the line of sight. If these displays are routinely scanned, the problem may not be significant. However, for those outside the normal scan pattern, special precautions should be taken. For example, a display may be located outside the normal scan pattern. It may contain system status information, which is usually in tolerance. The information on the display only becomes critical when a tolerance limit is exceeded. If the display were centrally located, red could be used to alert the operator. However, red is poor when used as a peripheral cue. What should be done? Several color coding possibilities exist. The most straight-forward one would be to use a central master warning light. Another solution would be to display the warning light or abbreviated message directly on the primary display.

8.15.5 Selecting Specific Colors

Where color is to be used as part of a display code, the designer must determine (1) how many different colors will be used, and (2) what these colors will be.

8.15.5.1 How Many Colors Should Be Used? The decision to use a given number of colors must be made after considering the limitations of the display medium, the ambient lighting, and perceptual limitations of the observer or display operator.

Factors influencing number of colors include:

a. Surface colors vs. self-luminous displays.
b. Ambient illumination.
c. Operator workload.
d. Color code relation to operator task.

8.15.5.2 Display Medium. Self-luminous displays such as CRTs may or may not have a limit on the number of different colors possible. As the number of colors used increases, the demands on the system for precise reproduction of each color increase. The more similar two colors are, the more critical it is that each be precisely defined and reproduced on the display. The probability of operator error will increase if color control is not fairly rigid, due to confusion as to which color is being displayed. In Table 55 (Connolly, Spanier, & Champion, 1975) examples of some common color confusions are presented. These confusions occur only for adjacent colors in the spectrum (see also Rizy, 1967).

Table 55

Errors of Color Identification

Shown	Called					
	Red	Orange	Yellow	Green	Total	Percent
Red	X	21	0	0	21	2.9
Orange	9	X	10	0	19	2.6
Yellow	0	6	X	15	21	2.9
Green	0	0	6	X	6	0.8
					67	2.3

8.15.5.3 Human Perceptual Limits. With very extensive practice and under ideal conditions, human observers can individually identify up to 50 colors (Hanes & Rhoades, 1959). This number, however, far exceeds any reasonable number for operational conditions outside of the laboratory. With less practice, but under laboratory conditions, it has been found that, as the number of colors increased, the number of identification errors also increased:

Number of Colors	Percent of Incorrect (Error) Responses
10	2.5
12	4.5
15	5.4
17	28.6

If the operator task requires absolute identification of a color, five colors appears to be maximum for high accuracy; 10 colors are acceptable if minor errors are permissible. If absolute identification is not required, more colors can be used.

8.15.5.4 Number of Colors vs. Performance. As the number of colors is increased in a situation where symbol color is assigned a particular meaning, both error rate and detection time increase. The general relationship between code size (e.g., number of colors) and response time is shown in Figure 217 (Teichner & Krebs, 1974). The greatest effect occurs early in training and diminishes with extended practice. This figure clearly shows, however, that the greater the number of colors used, the more time is required to respond to any individual color when it appears.

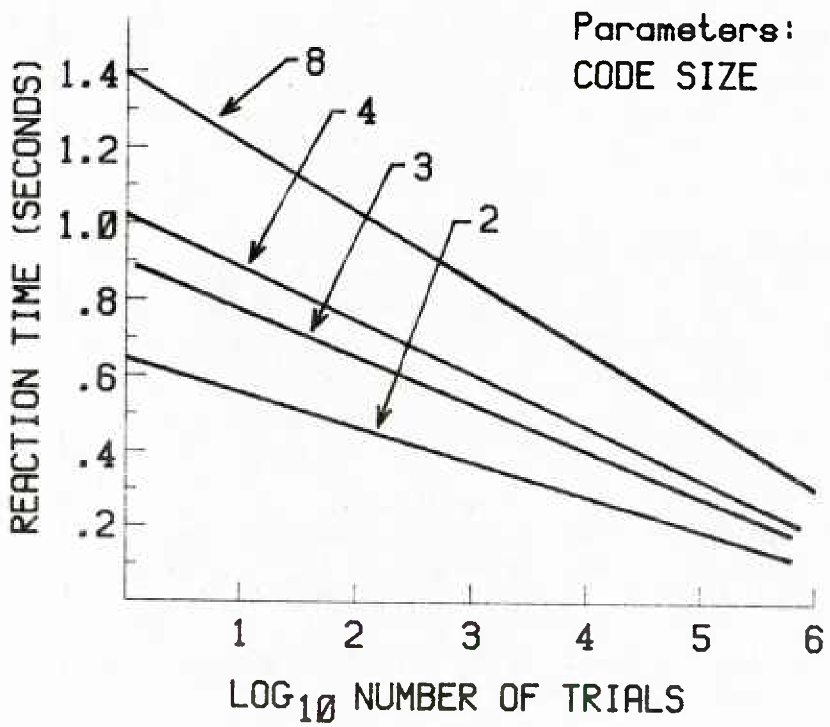


Figure 217. Reaction time as a function of practice for four code sizes with equally probable alternatives.

Similar relationships have been reported by Hitt (1961), who averaged the number of responses per minute over a variety of tasks involving multiple targets (Figure 218). When fewer colors are used, the response time will be faster for each one when it appears.

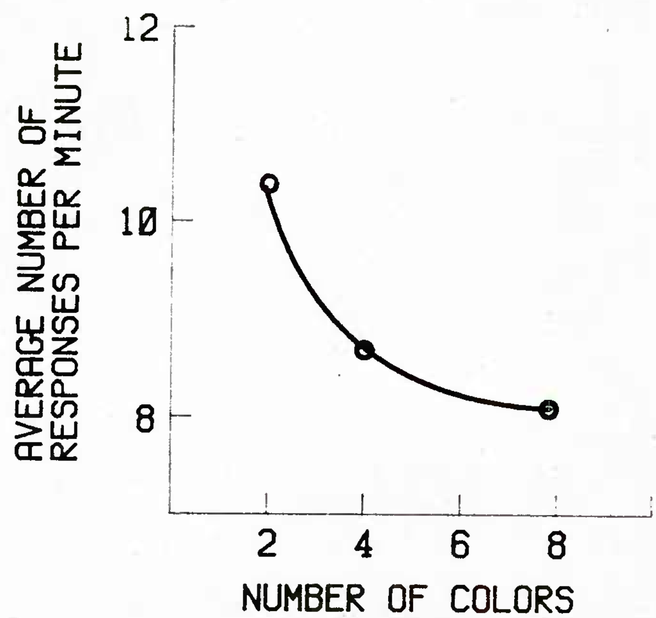


Figure 218. Effect of number of code levels on operator performance.

The importance of increased response time (or increased errors) must be related to the operator's task. If the workload is expected to be high or fast reaction time is critical, then the number of colors used should be kept as low as possible.

8.15.5.5 General Recommendations. Although no specific data appear to exist from real-world displays, several investigators (Haeusing, 1976; Semple et al., 1971) have recommended that a three-to-four color limit be used for operational displays. The smaller code size for operational situations is based on the expectation that ambient lighting may at times be high, that display reliability may be limited, and that fast reaction time of the operator may often be critical.

8.15.5.6 Which Colors Should Be Used? The best general criterion to use in selecting a set of colors of specified size is to pick colors as widely spaced in wavelength as possible along the visible spectrum. Under good viewing conditions, the 10 colors indicated in Table 56 (Baker & Grether, 1954) provide a highly identifiable set. The criteria for selecting a specific color set are:

a. Maximum wavelength separation.
b. High color contrast.
c. High visibility in specific application.
d. Compatibility of use with conventional meanings.
e. Legibility and ease of reading.
f. High saturation.

However, the limitations of hardware, the effects of ambient illumination, and operator workload may reduce this number somewhat.

Table 57 presents a six-color code recommended by Cook (1974) and also provides several notations helpful in identifying each color.

Table 56

Ten Colors that can be Identified Correctly Nearly 100 Percent of the Time Under Good Viewing Conditions

Dominant Wavelength (nm)	Color Name
430	Violet
476	Blue
494	Greenish-blue
504	Bluish-green
515	Green
556	Yellow-green
582	Yellow
596	Orange
610	Orange-red
642	Red

Table 57

Recommended Colors for a Six-color Code

Color Name	Munsell Notation	Chromaticity Coordinates	Dominant Wavelength (nm)	Federal Spec. 595 Equivalent (paint chips)
Purple	1.0 R P 4/19	X - 0.2884 Y - 0.2213	430	27144
Blue	2.5 P B 4/10	X - 0.1922 Y - 0.1673	476	15123
Green	5.0 G 5/8	X - 0.0389 Y - 0.8120	515	14260
Yellow	5.0 Y 8/12	X - 0.5070 Y - 0.4613	582	13538
Orange	2.5 Y R 6/14	X - 0.6018 Y - 0.3860	610	12246
Red	5.0 R 4/14	X - 0.6414 Y - 0.3151	642	11105

8.15.5.7 Relative Visibility of Individual Colors. All colors are not equally visible. The best documented example of this is the color blue. The fovea of the human eye, which is sensitive to detail, is essentially blue-blind (Wald, 1967). As a consequence, small symbols or fine detail are not seen as well in blue. Because of this, blue is not recommended as a color to be used for alphanumerics, lines, etc., unless they are unusually large.

Relative legibility of seven colors (including white) as a function of symbol size is shown in Figure 219. The data (Rizy, 1967) show the speed at which alphanumerics can be read as a function of symbol color and size. Under the conditions of this test red, white, and yellow symbols were read at a much higher rate than cyan (blue-green), green, or blue symbols. Similar data (Rizy, 1967) are shown in Figure 220.

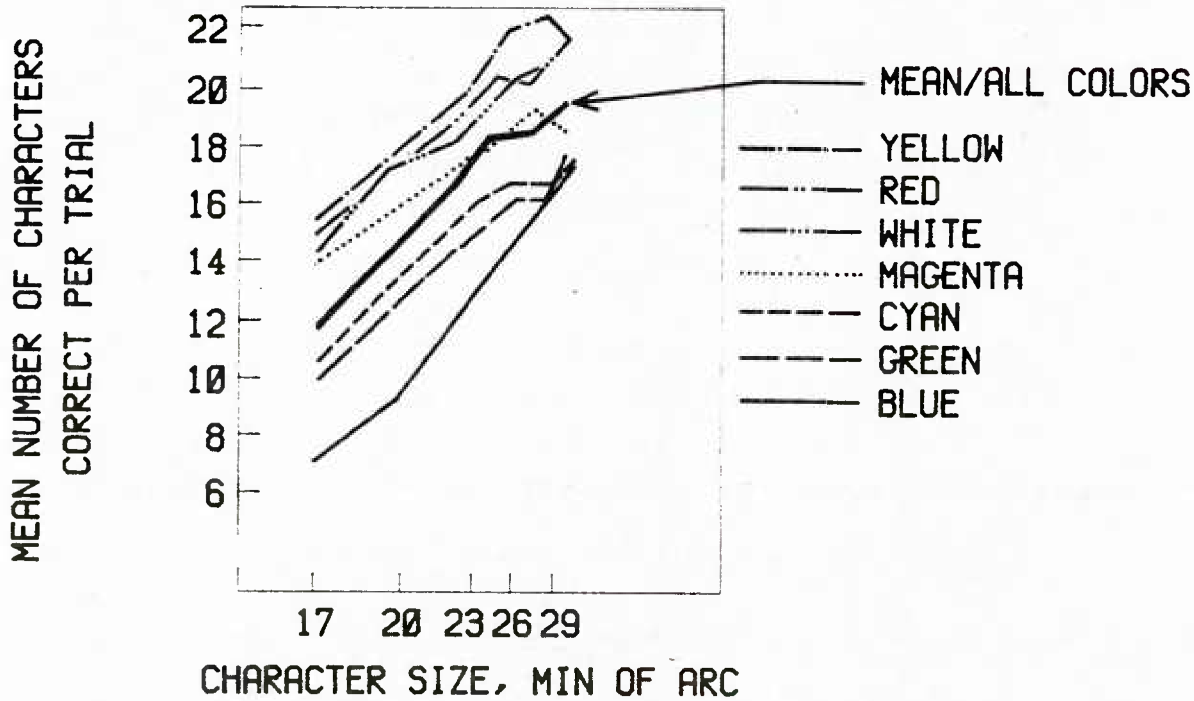


Figure 219. Performance in reading color-coded alphanumerics as a function of size and color.

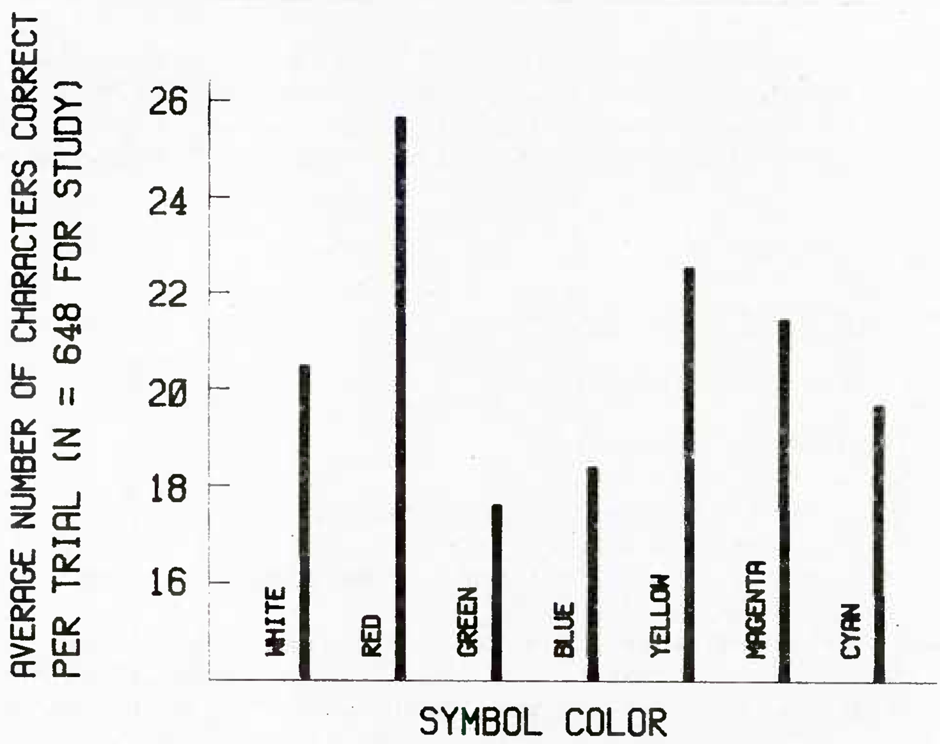


Figure 220. Reading accuracy as a function of symbol color.

Specific color recommendations for CRT displays are:

a. Use no more than four colors, if at all possible.
b. Use red, green, and yellow to code alphanumerics.
c. Use blue for large symbols or where symbol identification is not a problem.
d. Use conventional color code when appropriate.
e. Use white for peripheral signals.

8.15.5.8 Use of Saturation Difference in Color Coding. Use highly saturated colors (hues) to maximize the differences between colors. In some situations, it may not be possible or desirable to use highly saturated colors alone. One major reason for adding saturation as another color dimension would be to increase the number of color steps achievable with a particular display medium. For example, if the designer had only a two-color display, it might be possible to use saturation differences to produce more than two discriminable steps in the color code. A red-green display could then become a four-color display by producing a high and low saturation version of each color. Thus, red would become red and pink, and green would become light and dark green.

Saturation differences are used to produce the many color variations on maps and other printed (surface) color materials. Hue-saturation combinations can provide a large number of discriminable different values for the color code.

Caution should be taken to ensure that the changes in saturation do not produce colors that are difficult to see under some viewing conditions. High ambient illumination on the surface of the display will, itself, tend to desaturate or wash out the color of a symbol. If the symbol is already desaturated its visibility may be seriously degraded. If tight control of the ambient lighting is not exercised, the operator's shadow may cause the low-saturated (shadowed) display to appear the same as the high-saturated (unshadowed) display.

If ambient lighting can be controlled in those situations where the display is to be used, saturation level may provide a good method of increasing the color code size. If lighting will vary widely, use saturation level change only with caution. The visibility of desaturated colors under all levels of expected ambient lighting should be tested prior to use.

8.16 Color Coding Principles

8.16.1 Benefits of Color vs. Other Codes

Color coding will be helpful if:

a. The display is unformatted.
b. Symbol density is high.
c. Operator must search for relevant information.
d. Symbol legibility is degraded.
e. Color code is logically related to operator's task.

When used appropriately, color coding can provide significant performance improvements compared to other codes. It is clear from the available research literature that the relative effects of color coding are strongly determined by the specific function being served by the code. There are situations in which color is clearly superior to other codes. In other situations, color is significantly inferior as a code. One major factor that determines the relative merits of color coding is the task performed by the operator.

Results of two code comparison studies (Hitt, 1961; Christner & Ray, 1961) demonstrate that color coding is clearly superior to numbers, shapes, or letters when the task involves locating targets in a cluttered field of nontargets. Numeric coding is superior for identification tasks. Both the numeric and color codes are beneficial in a counting task. The remaining tasks (comparing and verifying) showed no specific advantage for any of the codes.

In summary, use color:

a. To aid operator in locating particular information.
b. To draw attention to some specific place or symbol.

Use alphanumerics:
a. To convey specific status information.
b. To identify specific targets.

8.16.2 Color Used in Conjunction with Other Codes

Use multidimensional coding:

a. To convey specific information that cannot otherwise be conveyed.
b. To increase the amount of information that can be displayed.

On any complex display, a number of coding dimensions are typically combined to convey specific information. Color can be used in combination with alphanumerics, shape, symbol orientation, symbol size, and symbol brightness to provide additional information or to make existing information easier to see or use.

If the particular color of a symbol is correlated with a value or values on another dimension, then color is a redundant dimension. Full redundancy occurs when this correlation is perfect (i.e., knowing the value on one dimension, completely determines the value on another dimension). If this correlation is not perfect, as in the case when fewer values are used on one of the two or more dimensions, there is partial redundancy.

An example should help to clarify the meanings of full and partial redundancy. A hypothetical digital readout has nine possible values it can assume. If color were fully redundant with numeric value, then each of the nine digits would be associated with one of nine different colors. Knowing the color of the symbol would provide full knowledge of the numeric value and vice versa.

If, however, several numbers were associated with the same color such that, for example, the three lowest values were coded yellow, the three middle values green, and the three highest values red, then the color code would be partially redundant with the numeric code. That is, knowing the symbol color would give only partial information about its numeric value. Knowing that the symbols displayed were green would indicate that the numeric value was one of three intermediate values.

A third form of multiple coding involves use of two or more codes in a situation where each conveys unique information not contained in the other codes. Such coding is nonredundant.

Use fully redundant coding:

a. To improve symbol detectability (locating symbols).

b. To aid in discriminating among symbols (full redundancy is an aid in reducing the possibility of confusion errors).

Use partially redundant coding:

a. When information can be categorized at more than one level of specificity.

Use nonredundant multiple coding:

a. To increase the total number of identifiable categories.

8.16.3 Nonredundant Use of Multiple Codes

Nonredundant color coding can be used to increase the number of symbols that can be absolutely identified on a display. Several studies (Ericksen, 1954; Garner & Creelman, 1964) have reported improved ability to discriminate among objects when size and color, or size, color, and brightness were combined into a single display than when any were used alone.

Practical applications of nonredundant coding include, for example, the coding of friendly and enemy "targets" on a map, sensor display, or air traffic controller's display. Targets could be coded by color as either friend or foe. Further distinctions as to target type (aircraft vs. ships) could be coded by shape. Specific targets within a type could be coded alphanumerically. Using such a system, a large number of targets could be uniquely coded in such a way that each is absolutely identifiable.

8.16.4 Use of Totally Redundant Codes

Symbols may be difficult to discriminate because the display is degraded by noise or poor luminance contrast, etc., or they may be difficult to locate because of clutter. In such situations, color may be used as a totally redundant dimension to improve symbol discriminability. Targets that can be defined on several dimensions are found more quickly than when either dimension is used alone. Color and shape have been found to be the best combined code. Other dimensions such as brightness and size were not as effective (Ericksen & Hake, 1955; Saenz & Riche, 1974).

8.16.5 Use of Partially Redundant Codes

When color is combined with, for example, an alphanumeric code, such that groups of numbers or letters are similarly colored and several groups are defined in terms of specific colors, then color is a partially redundant dimension. Such combined coding is used to provide relative status (using color) and specific status (using alphanumerics). For example, radiation exposure could be coded as high, in-tolerance, or low, using a three-color code such as red, yellow, and green respectively. Actual absolute radiation exposure would be given digitally. Depending upon present information requirements, a quick glance at the display would inform the operator of relative radiation exposure. Specific information would be available, if required, by the numeric value. Such multiple coding would be useful only in situations where both general and specific status information are meaningful at different times.

8.16.6 Color as an Irrelevant Coding Dimension

When a color code is irrelevant to the operator's task:

a. Symbol color serves to distract operator.

b. Similarly colored items may be visually grouped in nonmeaningful or distracting ways.

c. Color can functionally become "noise."

Two important principles are:

a. If the operator's task is easy and/or the display is uncluttered, color provides no performance benefits.

b. If the task is difficult, color coding must be appropriately related to the operator task to have value. If it is not related, it can degrade performance by serving as a distractor.

Color coding in high density displays:

a. Reduces search time:

(1) If target position is unknown, and
(2) Target color is known.

b. Increases search time:
(1) If target color is unknown.

8.16.7 Effects of Displayed Symbol Density

Display density refers to the number of symbols on a display. When the display is unformatted to the extent that target position is unknown, the nontarget symbols serve as distractors. If symbols are similar (e.g., all alphanumerics), the operator may have to examine each symbol to determine whether or not it is a target. Green, McGill, & Jenkins (1953) reported search times approximately equal to one-fifth of the total number of symbols. When color coding was added, search times were reduced to one-fifth of the number of alternatives of the target color.

The relationship between accuracy of locating targets and display density is shown in Figure 221 for two viewing times (Dyer & Christman, 1965).

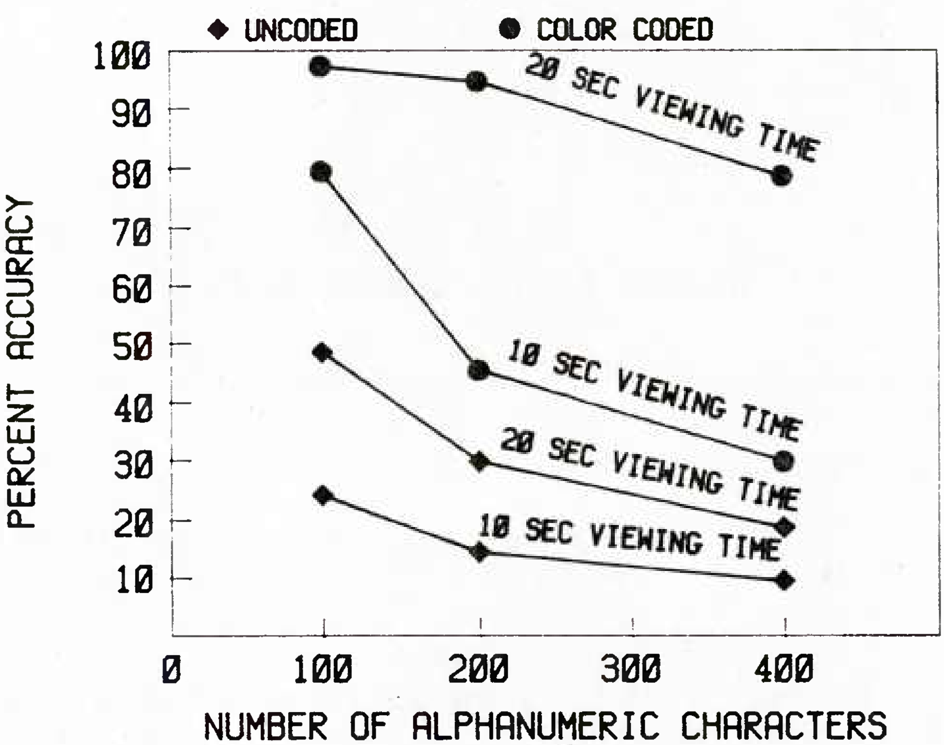


Figure 221. Effect of density and display exposure time on accuracy.

To be effective as a code, the color of the target must be known. Without this knowledge, multicolor displays may only distract from performance. This relationship is shown in Figure 222.

In Figure 201, a comparison between color coding and several shape codes was plotted as a function of symbol density (Wolf & Zigler, 1959). The fewest counting errors occurred using color coding. The relative superiority of color coding becomes more pronounced as symbol density increases.

Use color coding to reduce the effects of high symbol density:

a. By presenting functionally related items in the same color, or

b. By presenting "target" data in a unique prespecified color (e.g., warning light).

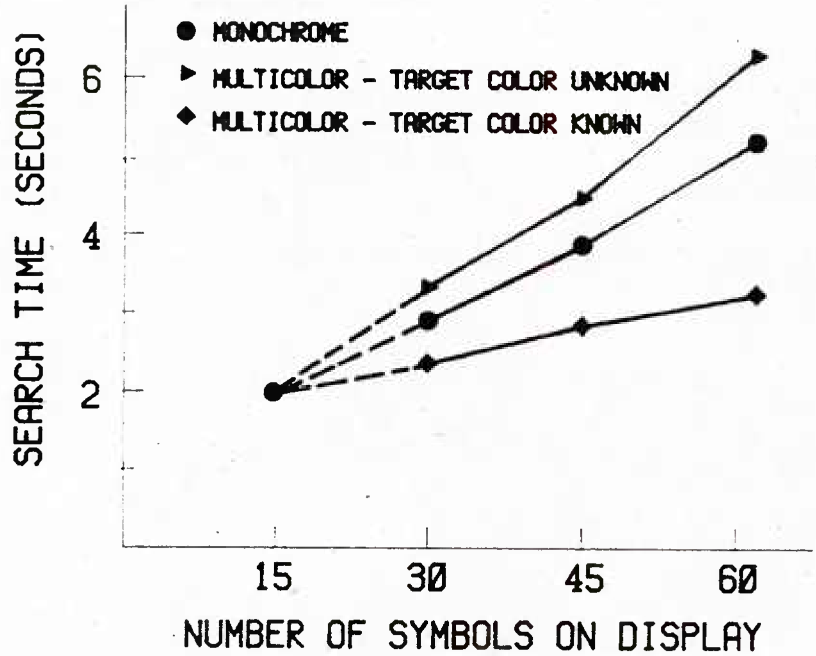


Figure 222. Effect of color coding as a function of display density.

8.16.8 Coding of Multiple Display Sets

When the operator has not one, but many color displays in a set, the principles discussed earlier apply not only to each display, but also to the set of displays as a whole.

8.17 Summary Recommendations

a. Color is recommended for coding alphanumeric displays under any of the following single or combined conditions:

(1) Density—100 or more characters.
(2) Display exposure time--10 seconds or less.
(3) Complexity--10 percent or more.

b. In addition, choose colors that indicate specific and consistent functions.

c. In choosing the type and amount of information to color code, avoid creating unplanned or obvious new patterns on the screen.

d. Patterns of color on the CRT face can either impede or enhance operator performance. Test each format for distracting visual noise before finalizing the color-code assignments.

e. If a pattern of color is intended to display a function, select colors that indicate the state of the system. Use muted colors for filling in symbols and unit markers on scales.

f. Color coding is beneficial if:

(1) The display is unformatted (i.e., not arranged in tabular format).
(2) Symbol density is high.
(3) Target position is unknown but the color of the target is known.
(4) Symbol legibility is degraded.
(5) Color is logically related to the operator's task.

g. Use color to indicate current status.

h. Have a very good reason for allocating color to a particular function (e.g., culturally engrained habit such as red for danger).

i. Use white for very important data and information presentations (white uses all three guns in the CRT and has high contrast on black background).

j. Use color as a redundant coding device.

k. Select colors with high contrast for parameters and features that must "catch" the operator's attention.

l. Simulate lighting conditions under which the display will be operated.

m. Colors will be distorted if colored ambient illumination is used (for reflectors primarily).

n. High ambient illumination can wash out colors.

o. Hoods that block out light and glare are helpful when ambient illumination cannot be controlled.

p. Do not use high-pressure sodium as an ambient-light medium for CRT viewing.

q. Color should indicate function according to the operator's mental set. For example, a layman's reaction to red (DANGER/STOP) would be different than a power plant operator's reaction (circuit on).

r. MIL-STD 1472C recommends the following color code:

Color	State	Result
Flashing Red	Emergency	Immediate user action.
Red	Alert	Corrective/override action must be taken.
Yellow	Advise	Caution; recheck is necessary.
Green	Proceed	Condition satisfactory.
White	Normal Transitory function	No "right" or "wrong" indication.
Blue	Advisory	Should be avoided or used only as background hue.

8.18 Disadvantages of Color Coding

a. The average color-normal person can discriminate only about nine hues of surface color on an absolute basis under ideal conditions and even fewer under adverse conditions.

b. Some people are color-defective; about 8 percent of all males and .4 percent of all females.

c. Color discrimination is seriously degraded when surface colors are viewed under highly chromatic light sources.

d. Even with recent improvement of color phosphors for use on CRT type displays, the presentation of satisfactory colored symbols by electronic means in video displays still presents technical problems. The difficulty arises from the effort to combine a number of parameters (e.g., very high resolution, no flicker or smear, dynamic data, etc.).

e. Character and stability of the display environment is difficult to create and control. Color judgments are influenced by many aspects of the surrounding conditions. Homogenity of background, color, and intensity of adjacent areas, differences between expected and actual conditions of illumination, perceived location of color relative to its surround, and the visual impressions that colors are abstract or attached to an object are examples of these factors.

f. All color coding methods present practical problems in maintenance. Surface colors have a tendency to fade with age. Signal lenses may crack, fade, or become obscured by dirt. Electronically generated color symbols are subject to distortion and (color) noise bursts and to effects of aging phosphors.

g. Signals or color patches of small dimensions, 20 minutes or less in visual angle, cause normal subjects to show certain characteristics of anomalous color vision. Color codes recommended for 2 degrees or larger do not apply to 20 minutes or smaller sources of light.

h. Reading performance for color coded displays deteriorates when contrast levels drop below 10:1, particularly for colors at the blue end of the spectrum. Above this level, the use of color coding tends to reduce the overall contrast level required for the display.

i. Reading performance for color coded displays is affected by the angular size and color of the symbology as shown in Figure 219. This study was done with a slide projector where the three primary colors were not independent; results may be somewhat different with a 3-gun CRT where the primaries are independently generated.

j. In displaying color additive displays, misregistration should not exceed 65 percent of stroke width (see Figure 223). This, however, is under relatively ideal laboratory conditions. For operational use, a more suitable value would be 50 percent. The greatest impact of misregistration occurs with white, cyan, and yellow (Figure 224).

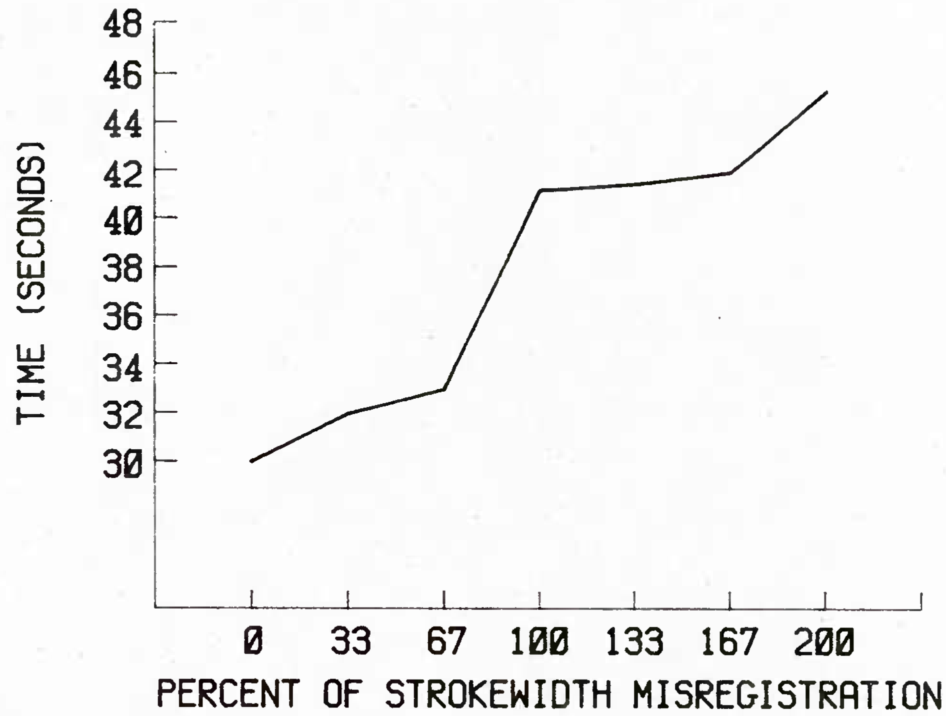


Figure 223. Response time as a function of misregistration (Snadowsky et al., 1964).

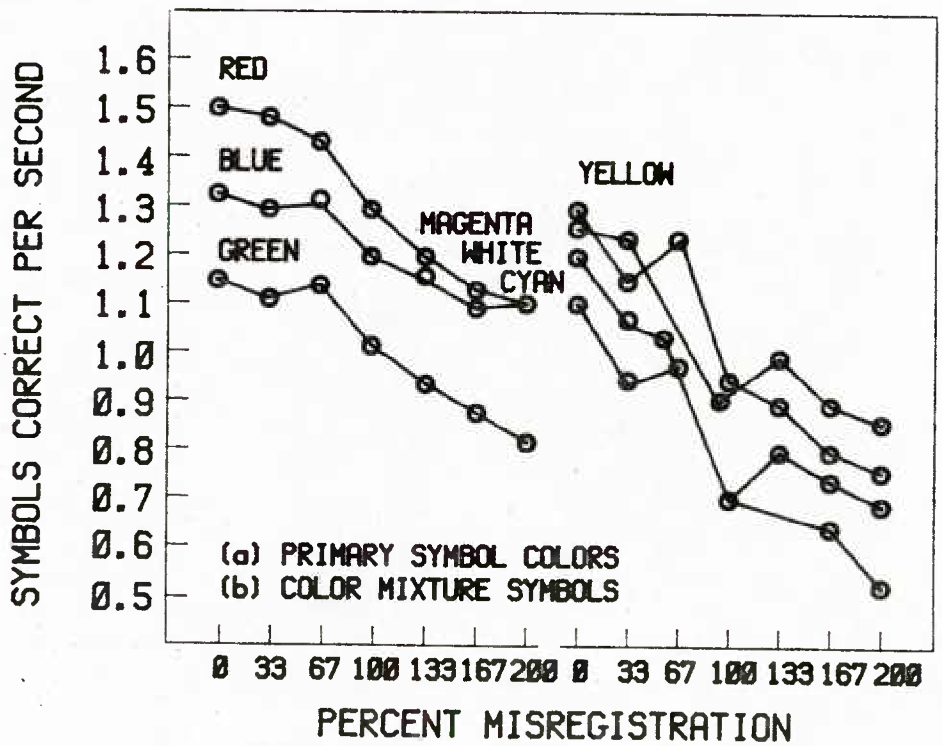


Figure 224. Viewer performance as a function of misregistration and symbol color (Snadowsky et al., 1964).

SECTION 9

ENVIRONMENTAL EFFECTS

9.0 ENVIRONMENTAL EFFECTS

9.1 Introduction

In the command and control environment, only certain environmental variables can be expected to affect human performance with regard to displays. These are:

a. Ambient illumination.
b. Noise.
c. Temperature, humidity, and ventilation.
d. Vibration.

Man's tolerances to these factors are shown in Table 58. Of these environmental factors effecting human visual performance, ambient illumination has been discussed as it relates to each of the classes of displays described earlier.

Table 58

Environmental Tolerances

Item	Tolerable Zone Lower Limit	Tolerable Zone Upper Limit	Danger Zone Lower Limit	Danger Zone Upper Limit
Temperature	$65^{\circ}F$	$75^{\circ}F$	$30^{\circ}F$	$100^{\circ}F$
Humidity	30%	70%	10%	90%
Ventilation	13 cfm	20 cfm	5 cfm	50 cfm
Illumination	20 fc	100 fc	-	10,000 fc
Noise	0 dB	85 dB	-	94 dB
Vibration	0.0005 in.	0.1 Hz	0.05 in	10 Hz

Note. From Air Force Systems Command, 1969.

In addition there is a special environment--the ocean--which imposes special requirements for visual displays and affects operator performance with those displays. It is not known how many CRT or other electronic displays are used underwater, but the available material will be presented as an aid to the design of any display to be used subsurface.

9.2 Noise

Operator efficiency on tasks involving vigilance over long time periods is reduced in noise environments of the order of 100 dB. Levels of noise above 90 dB degrade performance of multiple-choice, serial-reaction tasks.

9.3 Temperature/Humidity

While prolonged exposure to high ambient temperature/humidity will have a degrading effect on visual performance, the likelihood of the temperature/humidity conditions existing for sustained periods in the command and control environment is very small, rendering a detailed treatment of this area unnecessary.

For those instances where temperature/humidity exceeds the tolerances set forth in Table 58, attention should be given reducing operator duty cycles to compensate for the reduced vigilance performances occurring as function of adverse temperature/humidity conditions.

9.4 Vibration

High-frequency, low amplitude vibration has an adverse effect on operator visual functioning. Visual acuity suffers in the range of 5 to 90 Hz and shows decrements related to specific frequencies at 15, 30, and 40 to 70 Hz (Harris et al., 1965).

Specifically, under daylight or high levels of artificial illumination, the reading of printed numerical materials is not affected by vibration amplitudes up to .02 to .04 inch. Under illumination designed to protect dark adaptation, tolerances would be much less. The effect of vibration on reading accuracy is shown in Figure 225. It should also be noted that to a certain extent the effects of vibration can be mitigated by increased display luminance (as long as the amplitudes do not exceed the tolerances given in Table 58) (Lovelace Foundation, 1968). Recommended exposure times for various levels of vibration are shown in Figure 226.

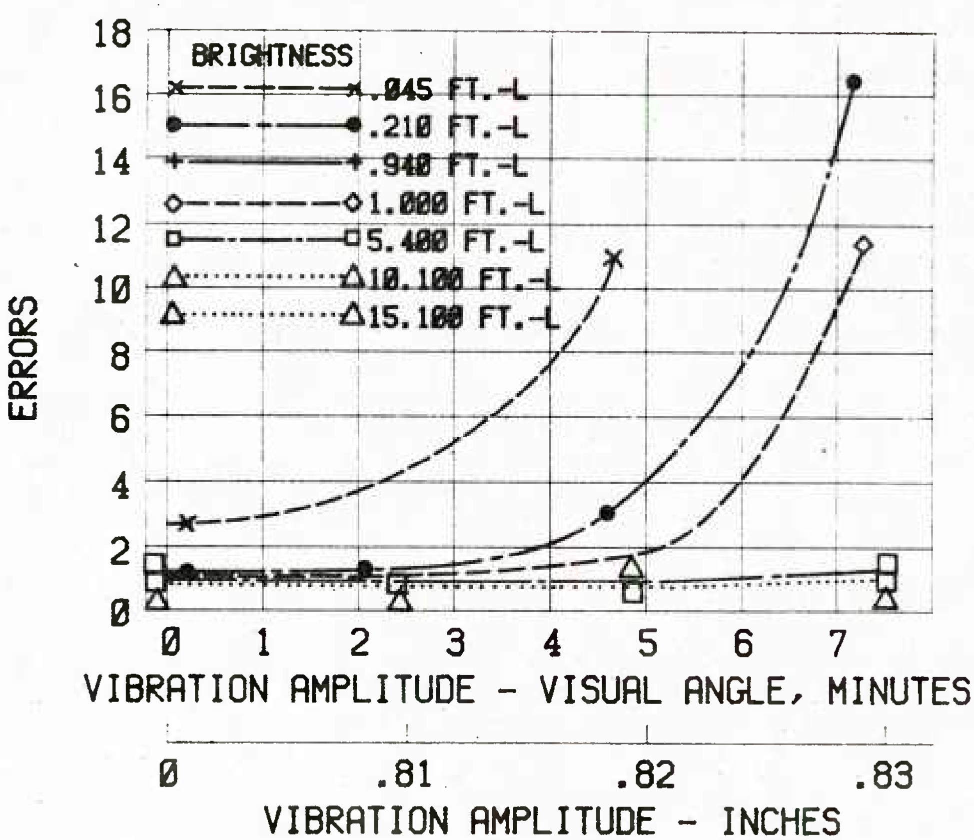


Figure 225. Effect of vibration amplitude (1050 cmp) on reading accuracy for various luminances.

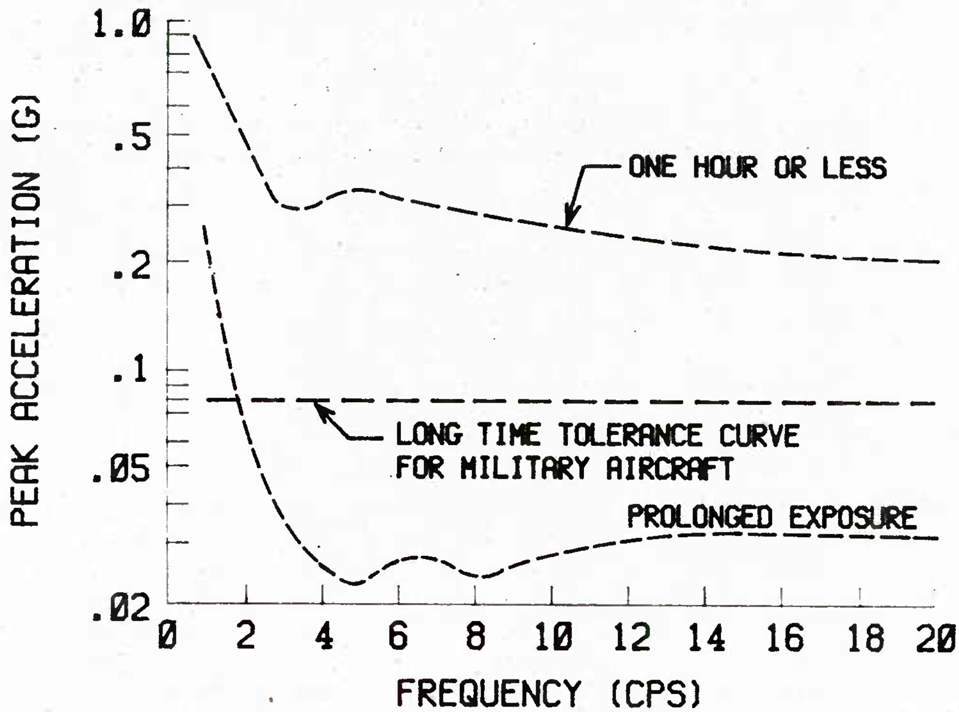


Figure 226. One hour and "long time" recommended limits of vibration exposure (Harris et al., 1965).

9.5 Human Engineering Guidelines for Design of Displays in Underwater Applications

The following material is taken from Vaughan and Kinney, 1981.

9.5.1 Eye-to-Console Distance

9.5.1.1 Problem Analysis. Seating arrangements and display console placements in aircraft and other vehicle systems that operate in air environments are designed for a 28 to 30 inch (71 to 76 cm) eye-to-console distance. This distance enables an operator whose arms are of shorter than normal length to reach panel controls.

In underwater applications, a 28 to 30 inch viewing distance is too long; many displays cannot be made bright enough to penetrate this distance of turbid water. Seating and console arrangements should enable the operator to be very close to his displays; particularly in turbid water environments such as harbors, rivers, and bays.

Instead of an arm length, the determining factor in design for eye-to-console distance is accommodation: the ability of the eyes to focus at close range and to hold this focus for several hours without experiencing eye fatigue. Accommodative capability is a function of age; younger eyes can focus very close objects and older eyes focus at progressively longer distances.

Eye fatigue during sustained, close-in visual work is difficult to demonstrate or measure. However, to guard against the possibility of eye fatigue, an accepted rule of thumb is to design so that the observer uses no more than half of his accommodative capability.

9.5.1.2 Translation Aids. Accommodation is measured as that distance away from the eyes where a visual stimulus shifts from blurred to clear. This measure is called the near point of accommodation.

Accommodative capability is usually expressed as an index in units derived from the near point measure. The index is called diopters of accommodation. A diopter (D) is the reciprocal of the near point in meters; that is,

$$D = \frac{1}{\text{Near point (m)}} \quad . \tag{9.1}$$

To apply the rule of thumb for fatigue-free, close-in visual work the following formula is used:

$$\text{Minimum viewing distance (m)} = \frac{1}{.5D} \tag{9.2}$$

or

$$\text{Minimum viewing distance (m)} = \text{Measured near point} \times 2 \tag{9.3}$$

Table 59 shows the average near point of accommodation and the minimum viewing distances for fatigue-free, close-in visual work for persons of different ages. Figure 227 illustrates these limits.

Table 59

Limits to Fatigue-Free, Sustained Visual Monitoring

Age	Accommodation Near-Point (m)	Diopters 1/Near-Point (m)	.5d	Rule of Thumb for Sustained Close-In Visual Work; Distance (m) = $\frac{1}{.5D}$
40	.25	4.0	2.0	.50 m
35	.18	5.6	2.8	.35 m
30	.14	7.0	3.5	.30 m
25	.12	8.5	4.25	.25 m
20	.10	10.0	5.0	.20 m

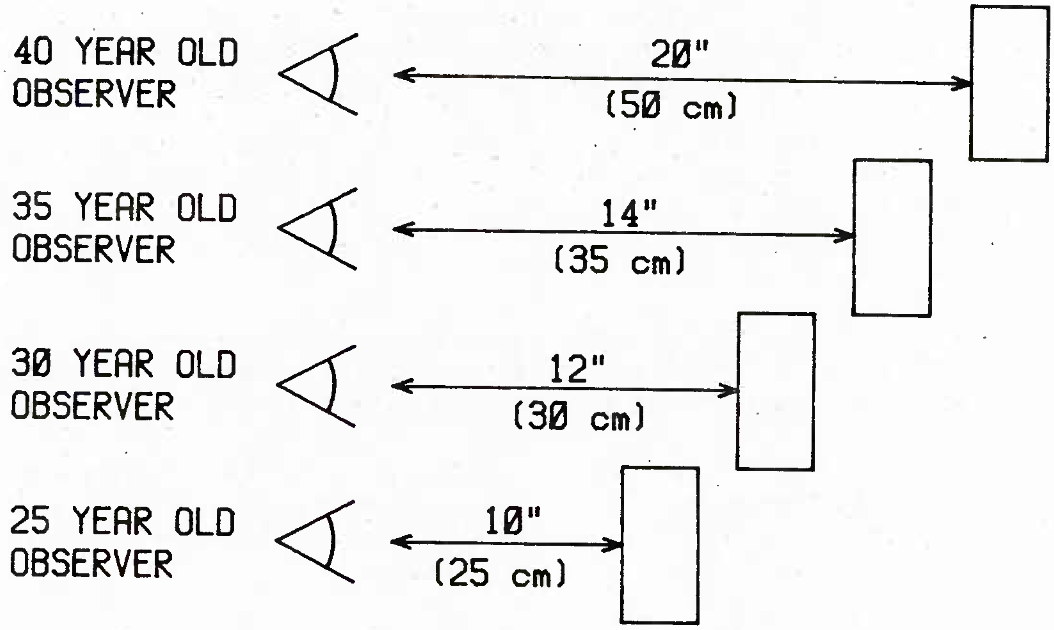


Figure 227. Limits to close-in, fatigue-free display monitoring. Design the seating and console arrangement so that diver can view displays comfortably with between 10 and 20 inches of eye-to-console distance, depending on his age. An eye-to-console distance of 14 inches is recommended as an optimum.

9.5.1.3 Recommendations. Design the seating and display console arrangements so that the diver can be comfortable and close to the displays for legibility in turbid water. A design that provides a range of eye-to-console distances between 10 and 20 inches will support long-duration, fatigue-free display monitoring by operators in the age range of 25 to 40 years.

9.5.2 Symbol Size

9.5.2.1 Problem Analysis. To a display manufacturer or designer, size is character height and width; but to the human visual-perceptual system size is visual angle (i.e., the size of the image being projected to the diver's eyes). Therefore, viewing distance and character dimension must be considered simultaneously to determine the effective perceptual size of alternative alphanumeric symbols. As a symbol is moved closer to the eye, its visual angle and, therefore, its perceived size increase.

In traditional applications, acceptable symbol size ranges between 10 and 20 minutes of arc. Smaller displays are acceptable under conditions of high luminance; larger displays are more appropriate for low levels of luminance. This is because

luminance and size combine to affect legibility; within limits, equivalent legibility can be achieved by using higher luminance with small displays, and lower luminance with large displays.

The size vs. luminance interaction is particularly important for achieving uniformly bright readouts on a console for underwater applications. Smaller displays need to be of higher luminance than larger displays to appear equally bright.

Self-luminous alphanumeric symbols need to be larger and/or more luminous for legibility underwater as compared to air viewing environments, mainly because of the differences in contrast. Most bodies of water are turbid to some degree and the suspended particles scatter light away from the eye, reducing luminance contrast between the display and its background.

9.5.2.2 Translation Aids. Manufacturer's catalogs describe display size by character height and width. The "size" that affects legibility, however, is visual angle; the size of the image at the eye expressed in degrees and minutes of arc.

Visual angle is a function of the symbol size and its viewing distance. It can be computed by a formula applicable to the small angles characteristic of displays on hand-held equipment and on vehicle consoles. Character height is the dimension typically used to define symbol size in the formula as follows:

$$\theta' = \frac{(57.3)(60)(h)}{d}, \tag{9.4}$$

where

θ' is visual angle in minutes,
h is character or digit height, and
d is viewing distance; h and d are in the same units.

Figure 228 provides a rough guide to digit size and viewing distance combinations that yield small (20 minutes of arc), medium (40 minutes of arc), and large (80 minutes of arc) visual angles as applied to symbol legibility underwater. At a typical viewing distance of 14 inches, a digit .08 inch high will appear small; one .16 inch high, medium; and one .32 inch high, large.

9.5.2.3 Recommendations.

a. Use alphanumeric symbols of a height whose visual angle lies between 40 and 80 minutes of arc.

b. Assuming a viewing distance of 14 inches, the recommended range of character height is from .16 to .32 inch. Extending the viewing distance to 18 inches expands this recommended range from .20 to .40 inch.

c. Do not use characters whose visual angle is larger than 80 minutes of arc since the improvement in legibility will be marginal. A character height of .50 inch is probably the largest symbol that might be required.

d. Do not use characters whose visual angle is less than 40 minutes of arc unless the application is restricted to clear water (i.e., open or coastal oceans). For these waters, use character sizes ranging from 20 to 40 minutes visual angle.

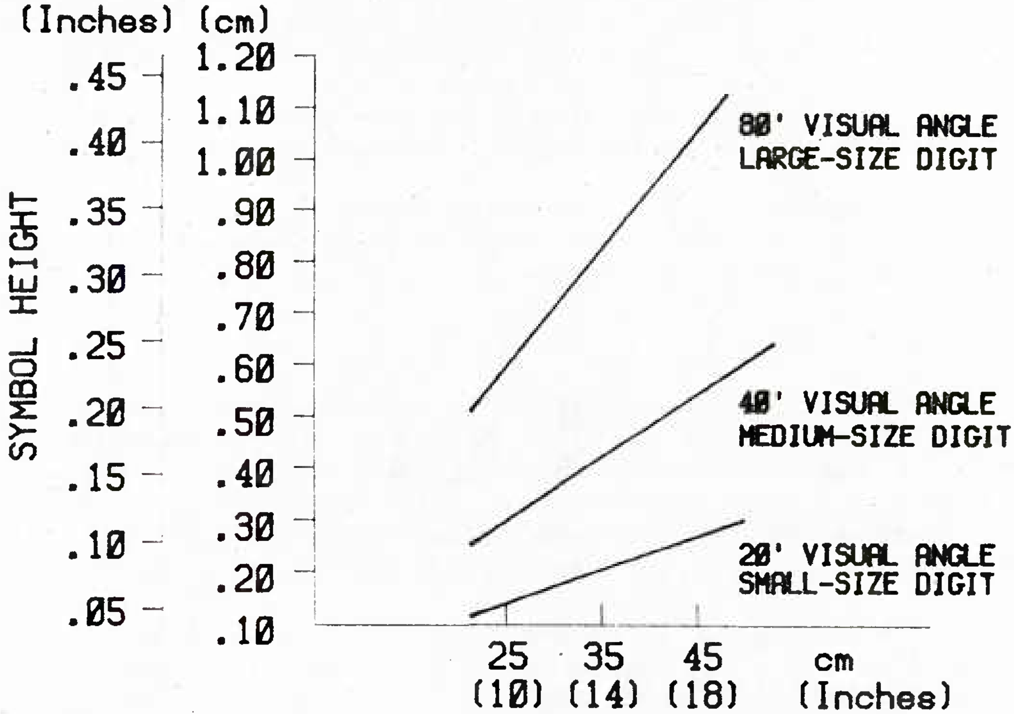


Figure 228. Combinations of symbol height and viewing distance that yield small, medium, and large visual angles.

e. In the size range 40 to 80 minutes visual angle, displays of approximately equal luminance will appear equally bright. If the panel includes symbols of disparate sizes (i.e., some 20 and some 80 minutes visual angle), the smaller units must be of higher luminance than the larger units in order to appear equally bright.

f. In general, display legibility in underwater environments is more effectively accomplished by increasing luminance than by increasing size.

9.5.3 Display Luminance

9.5.3.1 Problem Analysis. How much luminance a self-luminous or transilluminated display requires in order for the diver to see it clearly depends on five factors:

a. Ambient luminance. Is the water dark or illuminated? In the dark, display luminance is the determinant of legibility; in illuminated water, luminance contrast between the display and the background is the determinant.

b. Turbidity of the water. Particles suspended in the water reduce the amount of energy transmitted from the source to the eye.

c. Viewing distance. The farther the light has to travel, the less energy from the source arrives at the eye. This factor combines with turbidity effects to reduce light energy as it travels through the water.

d. Display size. Dimensions of the display element combined with viewing distance define a visual angle. Displays of large visual angles are more easily seen (i.e., require less luminance for legibility) than displays of small visual angle.

e. Display color. Depending on the turbidity of the water, the amount of light energy transmitted along a pathway will be a function of its wavelength or color.

Requirements for at-the-source display luminance increase as the level of ambient luminance increases, as the water turbidity increases, as the eye-to-display distance increases and as the visual-angle size of the display decreases.

9.5.3.2 Recommendations

a. In dark oceanic, coastal or bay water applications, provide for an adjustable display luminance in the range .5 to 20.0 cd per m^2. This assumes a display of any color between 20 and 80 minutes in visual angle size and a viewing distance of 18 inches or less. Table 60 shows specific values of display luminance required for clear legibility under a variety of conditions; note that all are within 20 cd per m^2. Also, levels of luminance adequate for an 18-inch viewing distance are adequate for closer distances.

b. In dark harbor water, provide for display luminance as shown in Table 61 for the combination of size, color, and viewing distance of the design application. Note the advantage of red light in harbor water.

c. In illuminated waters where luminance contrast determines legibility, use Table 62 as a guide. The general rule is that luminance at the eye should have a contrast ratio of .40 with ambient luminance at low light levels and .20 at high light levels. Formula for contrast ratio is as follows:

$$\text{Contrast ratio} = \frac{\text{Display luminance - background luminance}}{\text{background luminance}}$$

or

$$CR = \frac{DL}{BL} - 1 \qquad (9.5)$$

If ambient luminance is not measurable, use Table 63.

d. In harbor water, at shallow depths during sunlight conditions, source luminance requirements are very high and beyond the capability of technologies such as LED displays.

Table 60

Display Luminance (cd/m^2) Required for Clear Legibility in Dark Oceanic and Bay Waters at 45 cm (18 Inches) Viewing Distance

Water Type	Display Color and Size (Visual Angle)								
	Green Display			White Display			Red Display		
	20'	40'	80'	20'	40'	80'	20'	40'	80'
Clear ocean	3.4	1.5	.5	3.4	1.5	.5	3.8	1.6	.6
Coastal ocean	5.2	2.2	.8	5.2	2.2	.8	6.6	2.8	1.0
Bay	16.5	7.0	2.5	10.3	4.4	1.6	8.3	3.5	1.3

Table 61

Display Luminance (cd/m^2) Required for Clear Legibility in Dark Harbor Water

Display Size in Visual Angle	Display Color and Viewing Distance								
	Green Display			White Display			Red Display		
	10 In.	14 In.	18 In.	10 In.	14 In.	18 In.	10 In.	14 In.	18 In.
20'	330	1,650	11,000	165	825	4,714	83	660	3,300
30'	200	1,000	6,667	100	500	2,857	50	400	2,000
40'	140	700	4,667	70	350	2,000	35	280	1,400
50'	100	500	3,334	50	250	1,430	25	200	1,000
60'	70	350	2,334	35	175	1,000	18	140	700
70'	60	300	2,000	30	150	857	15	120	600
80'	50	250	1,667	25	125	715	13	100	500

Table 62

Amounts of Luminance (cd/m^2) Required for Clear Legibility in Illuminated Water

Ambient Water Luminance	Luminance Required At the Eye for Clear Legibility	Luminance Required At the Display Source for White Light At 14 Inches Viewing Distance			
		Open Ocean	Coastal Ocean	Bay	Harbor
3.4 cd/m^2	5	5.2	7.1	12.0	1,250
34.0	50	52.0	71.0	120.0	12,500
340.0	410	423.0	586.0	976.0	102,500
3,400.0	4,100	4,227.0	5,857	9,762.0	1.02×10^6

Table 63

Illuminance Levels at Operational Depths in Ocean and Harbor Waters for Two Conditions of Surface Illuminance (fc)

Type of Water	Depth (m)	Surface Illuminance (fc) Direct Sunlight 10^4	Overcast Day 10^2
Coastal ocean	5	2.0×10^3	2.0×10^1
	10	4.4×10^2	4.4
	20	2.6×10^1	2.6×10^{-1}
Harbor	5	2.1×10^2	2.1
	10	5.9	5.9×10^{-2}

9.5.4 Peripheral Location

9.5.4.1 Problem Analysis. In vehicle system applications, the operator's visual attention may often be demanded almost continuously by one critical display function. For example, the heading error display in submersibles, which is located in the center of the operator's console in direct line of sight. Other, less critical information is displayed in peripheral areas of the console, and the operator develops a visual scanning pattern to update his information about these other aspects of system status or mission progress. The designer's problem is to decide where on the console to place these secondary information displays relative to the centrally located primary display.

The shape of the useful visual periphery in underwater system applications is different from air environments due to exaggerated bending of light rays in the periphery caused by the change in velocity of light through water vs. air that occurs at the diver's faceplate.

9.5.4.2 Translation Aids. Research results about the usefulness of peripheral visual fields for one kind of visual task or another are typically reported in peripheral angle, off-axis angle, or eccentric angle. Basically, the angle referred to is the angle at A in Figure 229, where as elements in the peripheral display application:

A is the location of the diver's eyes,
B is the location of the peripheral display element,
C is the center of the console,
a is the distance by which the peripheral display at B is offset from the center console display at C,

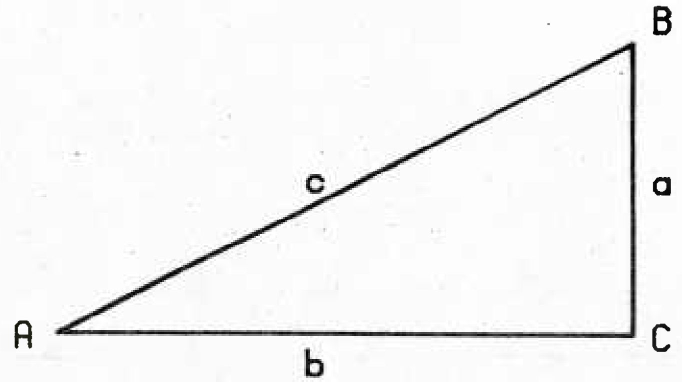


Figure 229. Elements in peripheral displays.

b is the direct, line of sight, zero eccentricity distance from the diver's eyes to the center of the console, and

c is the distance traveled by light from the peripherally located display to the diver's eyes.

The geometry of the peripheral display problem has three potential uses to the display designer in interpreting research results about peripheral visual fields and analyzing the problem of locating peripheral displays.

a. A recommendation is expressed as a peripheral angle, off-axis angle, or eccentric angle and the designer wants to translate this angle at the eye to a linear distance on the face of the console. The applicable trigonometric function for this problem is:

$$a = (b \text{ Tan } A). \tag{9.6}$$

b. The designer is considering a given linear displacement from the center of the console as a potential solution to a display location problem and wants to know the peripheral angle of that location. The applicable trigonometric function for this problem is:

$$\text{Tan } A = \frac{a}{b} \tag{9.7}$$

c. The designer wants to know the length of the light path from a peripheral location on the console to the diver's eyes. The designer will need this value to calculate required luminance of the peripherally located light. The applicable trigonometric function for this problem is:

$$c = \frac{a}{\text{Sin } A} . \tag{9.8}$$

Table 64 is a guide to translating eccentric angles and console distances into distance from the center of a console and distance to the eye of a peripherally located display.

Table 64

Distance (Inches) from Console Center (a) and Distance to the Eye (c) for Various Eccentric Angles (A) and Eye-to-console Distances (b)

Eccentric Angle At A	b = 10"		b = 14"		b = 18"	
	a	c	a	c	a	c
5^o	.9	10.3	1.2	14.0	1.6	18.4
10^o	1.8	10.4	2.5	14.4	3.2	18.4
15^o	2.7	10.4	3.8	14.7	4.8	18.5
20^o	3.6	10.5	5.1	14.9	6.5	19.0
25^o	4.7	11.1	6.5	15.4	8.4	19.9
30^o	5.8	11.6	8.1	16.2	10.4	20.8
35^o	7.0	12.2	9.8	17.1	12.6	22.0
40^o	8.4	13.1	11.8	18.4	15.1	23.5
45^o	10.0	14.1	14.0	19.8	18.0	25.5
50^o	12.0	15.7	16.7	21.8	21.5	28.1

9.5.4.3 Recommendations. Limits to the placement of display elements into the peripheral visual field depend on the visual task. For example, if the operator need only to detect the onset of a signal light, the light element can be located farther into the periphery than if he needs to read a word or a number.

a. If the display is a signal to be detected. Detection of peripheral signals is reliable and fast to a limit of a 47 degree eccentric angle when the signal light is in the blue/green to green color range. At an eye-to-console distance of 14 inches, a 47 degree eccentric angle is 15 inches from the center of the console. Display color is an important determinant of peripheral detection; blue/green and green light scatters and the diver detects a 'bloom' of light in the water. If nonscattering, red light were substituted for green in the previous example, the peripheral limit would be 9 rather than 15 inches of lateral displacement from the center of the console. Figure 230 illustrates the limits to peripheral location for signal detection.

b. If the display is numbers or letters to be read. An operator attending to a centrally located display can accurately read peripherally placed words or numbers to a limit of a 33 degree eccentric angle. At an eye-to-console distance of 14 inches, this angle translates to 9 inches of lateral displacement from the console center. Display color does not affect this recommendation; red numbers are as accurately read as green numbers at a 33 degree eccentric angle. Figure 231 illustrates the limits to peripheral location of alphanumeric displays for accurate reading.

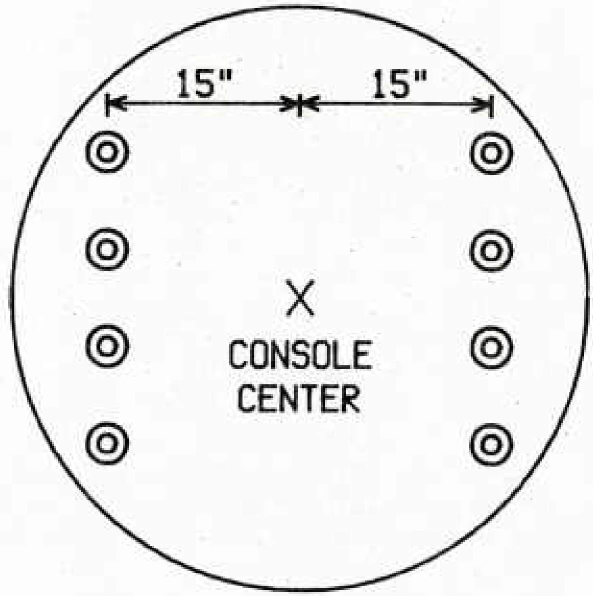


Figure 230. Detecting peripheral signals. Peripheral limits for fast, reliable detection of warning or alert-signals while the operator is attending to a central display. Signal lamps must be blue/green or green (500 to 540 nm) and of a luminance adequate for the turbidity condition, lamp size, and viewing distance.

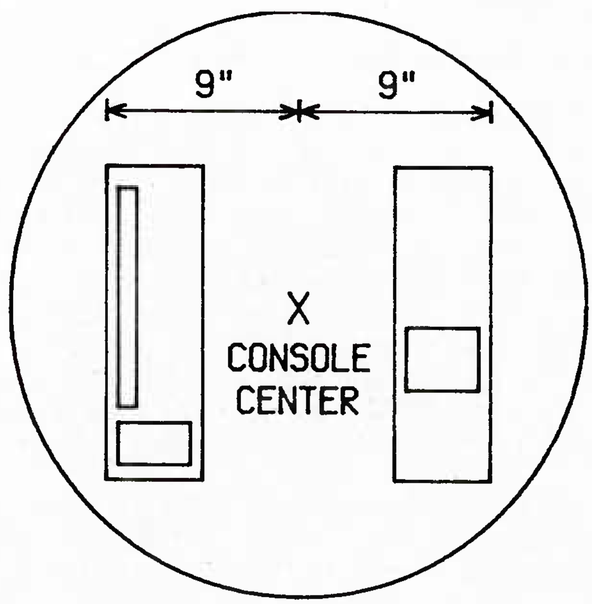


Figure 231. Reading alphanumeric displays in the periphery. Peripheral limits for > 96 percent accuracy in reading numbers, letters, words, and other symbols while operator is attending primarily to a central display. The visual scanning pattern requires eye movement only. Given adequate display luminance, color is not a factor in this visual task.

9.5.5 Use of Color

9.5.5.1 Problem Analysis. The use of color in underwater display applications is a more complex problem than it is in air. This is because air transmits all wavelengths equally well, while water is wavelength selective. Clear water absorbs longer wavelengths more than it does shorter ones (e.g., longer wavelengths, reds, are absorbed over a much shorter path length of water than the shorter, blue, wavelengths). Also, very small particles suspended in the water scatter light energy selectively by wavelength (short wavelength energy is reduced by scattering to a greater extent than is long wavelength energy). Consequently, any natural body of water will be maximally transmissive to a single wavelength depending on its particular turbidity characteristics. As light is transmitted through a natural body of water, its original spectral composition is progressively narrowed toward that wavelength to which the water is maximally transmissive. For example, sunlight penetrating the surface of the water tends toward blue-green in the open oceans, toward green in coastal ocean waters, and toward red in highly turbid inshore waters.

These physical phenomena have important implications for display design. One is that display color can be chosen to match the wavelength transmission characteristics of the operational water. Another consideration is that ambient light in the water will tend to be almost monochromatic (especially at greater depths), and, since the human visual-perceptual system adapts to monochromatic light, the color appearance of colored displays will vary according to the color of the ambient water.

9.5.2.2 Recommendations.

a. Color as an aid to search and detection of painted objects.

(1) The most luminous color of paint underwater depends on the spectral composition of the illuminating light. With natural illumination (i.e., sunlight penetrating from the surface) use blue-green paint in clear ocean water, green or yellow paint in coastal water, and orange or red paint in very turbid inshore water for maximum luminance. Where an object must be used in various waters, use white paint. White is always among the most visible paints since it reflects whatever wavelengths of light reach it through the water. Fluorescent paints tend to be more visible than regular paint since they convert very short wavelength energy into wavelengths where human vision is more sensitive. Note that the rules as stated yield colors that blend with the background (i.e., no color or luminance contrast). These colors are good if used as a background for signs and symbols that have high contrast with the painted background.

(2) When painted objects are to be illuminated artifically, the most visible colors depend on the spectral composition of the artificial illuminant. For example, mercury vapor lamps contain mostly short-wavelength energy and are good illuminants for blue and green paint. Incandescent lamps contain primarily long-wavelength energy, and so are good illuminants for yellow, orange, and red paints.

b. Color as an aid to legibility of self-luminous displays.

(1) In the majority of applications, the viewing distance will be short and color will not affect legibility; luminance will be the major determinant of legibility. There are exceptions, however. One is the use of red light in highly turbid water; a second is the use of color in illuminated water.

(a) In dark, highly turbid water environments such as bays, rivers, and harbors, red (640 nm) self-luminous digits or symbols are seen clearly at lower levels of luminance than any other color, even at short (10-inch) viewing distances. Also, red light does not scatter in turbid waters providing a measure of covertness which may be a concern in particular military contexts.

(b) In special applications where self-luminous symbols must be read in relatively shallow water during daylight (i.e., there is high ambient illuminance at the diver's operating depth), colors complementary to the ambient water color will be seen most easily.

(2) The recommended colors for self-luminous or transilluminated symbols, therefore, are also the complements of the recommendations for painted symbols under conditions of high ambient illuminance. Table 65 presents recommended colors for most legible lights and paints in natural waters illuminated by sunlight.

c. Color as an air to detection of peripheral signals. If differently colored signal lamps are of equivalent luminance, use short wavelength light, blue/green or green in color name, 500 to 540 nm in wave length. Greenish light is scattered by suspended particles, creating a bloom of light in the peripheral field that is quickly and reliably detected. This effect occurs even in the relatively clear water of the coastal oceans.

Table 65

Most Legible Color of Self-luminous and Painted Displays in Natural Waters Illuminated by Sunlight

Type of Water	Ambient Water Color in Sunlight	Most Legible Colored Lights for Self-luminous Displays	Most Legible Colored Paints for Painted Displays
Open ocean	Blue-green	Yellow Orange Red	Blue-green
Coastal	Green	Red	Green Ocean
Harbors, rivers, and bays	Orange-red	Blue-green Green	Orange Red

d. Color as a coding technique.

(1) Since display luminance is the primary determinant of legibility in underwater environments, the use of color as a coding device should be approached with the following cautions:

(a) Placing a color filter over a white light source always reduces its luminance to some extent.

(b) The amount of luminance reduction is a function of the energy distribution of the source and the spectral transmission of the filter. Source lamps are typically incandescent tungsten, most of whose energy is in the longer wavelengths (i.e., there is very little blue energy in the source and not much green). Since a color filter removes most of the energy at wavelengths other than that of the desired color, placing a blue filter over an incandescent lamp can potentially remove so much of the source luminance that the display is darkened below the threshold of legibility. Incandescent lamps with blue filters are quite dim unless the lamps are very powerful; then, the filters get very hot.

(c) Since different colored filters reduce the luminance of the source lamp in different amounts, the use of several colors on a display panel will make the colors vary in perceived brightness: reds and yellows, bright, green less so, blue, dim. What may be intended as color coding may result in brightness coding. Since a display design objective is to create panel readouts of equivalent brightness, different color elements may need to be differentially powered to achieve equal luminance through the filter or neutral density filters must be used with red and yellow filters.

(2) In illuminated waters, the color appearance of colored lights and of colored paints will be modified by the ambient hue in different ways:

(a) The color appearance of painted objects will be modified in the direction of the hue of the ambient light. For example, in coastal ocean waters, the ambient light will tend toward green; therefore, white paint will appear green, red will appear orange, orange will appear yellow, yellow will appear green, green paint will appear very green, and blue paint will appear a blue-green. In a harbor or other highly turbid inshore waterway, the ambient light from sunshine will tend toward red; therefore, white paint will appear red, red paint will appear very red, orange will appear red, yellow paint will appear orange, green paint will appear yellow, and blue paint will appear green or purple.

(b) The color appearance of colored lights on the other hand will tend toward the hue of the complement of the ambient light. For example, in coastal ocean waters the ambient light from the sun is filtered toward green. The human visual-perceptual system quickly adapts, and the ambient light as well as other green lights appear as a very low saturated green or as a neutral grey. The complement of green (i.e., red) is then added to the perception of other lights (e.g., white light appears red). Table 66 shows how a range of colored light commonly appears in dark and illuminated waters.

(3) The potential for color confusion is so great in systems that must operate in a range of underwater environments that color coding should be minimized. For reliable discrimination use only two colors--one from either end of the spectrum (i.e., a red and a blue-green).

Table 66

Color Appearance of Self-luminous Colored Displays in Different Environments

Display Wavelength (nm)	As Seen in Air	In Dark Water		In Illuminated Water	
		Coastal Ocean	Harbor/Bay	Coastal Ocean	Harbor/Bay
473	BLUE	BLUE	BLUE	BLUE	BLUE
503	GREEN	GREEN-blue	GREEN-blue	BLUE	BLUE
552	GREEN-yellow	GREEN-white	GREEN	WHITE	GREEN
579	YELLOW	YELLOW-white	YELLOW	RED-white	WHITE
608	RED-yellow	RED-white	RED-yellow	RED	RED
640	RED	RED	RED	RED	RED
ALL	WHITE	WHITE-yellow	YELLOW-white	RED-white	BLUE-white

SECTION 10

OPERATIONAL PERFORMANCE DATA

10.0 OPERATIONAL PERFORMANCE DATA

10.1 Introduction

If display designers had their wish, they would have error probability or probability of detection data for the major types of displays and display parameters (e.g., as a function of resolution, target size, etc). Although some data for individual parameters have been procured under laboratory conditions, almost none has been available for displays used in operational or quasi-operational situations. It is also extremely likely that any such data would be classified and could not be published for open distribution.

The following material can, therefore, be only illustrative of the detection probabilities one secures under operational conditions. It is provided to make designers aware of the significant influence the operator has on how adequately the total system performs. The data presented cannot be utilized as a design guide because it is peculiar to a single radar display that is obsolete by today's standards. The following is taken from Kinney (1968).

The AN/APS 88 radar was part of the sensor system for the S-2E aircraft. It was a lightweight ASW weather warning and general purpose search radar. The following are its pertinent characteristics: 8500 to 9600 Mc (X band) frequency; 65 kilowatt peak power; -105 dB minimum receiver sensitivity; pulse width, 0.35 millisecond; fan or pencil radar beam; 2.5 degrees, horizontal beamwidth; 28 rpm sweep rate.

The basic approach used for the analysis was to synthesize the existing empirical information and basic characteristics of radar detection into a detection model for calculating the detection performance of the AN/APS-88.

10.2 The Detection Model

The detection model is based on the concepts of blip-scan detection theory. In the blip-scan theory, the single-scan probability of detection is considered to be a product of:

a. The probability of a detectable blip appearing on the radar scope (the blip-scan ratio).

b. The probability that the operator detects a blip when it appears (the operator factor).

Blip scan ratio vs. range curves for the AN/APS-88 radar are used with the model to calculate detection performance.

The effect of the operator's performance is illustrated by calculating, with the detection model, detection probabilities against submarines with three different levels of operator performance:

a. Perfect operator--all target blips displayed are detected (this is a threshold type detector).

b. Attentive operator--the operator is attentively observing the scope, but the probability of detecting a displayed blip is a function of the blip strength (dependent on signal/noise).

c. Inattentive operator--blip detection is a function of blip strength, but the operator is effectively searching the scope only a fraction of the time.

The second case is actually the normal search operator under ideal conditions. For the attentive operator, empirical operator characteristics reported by the Naval Research Laboratory were used. These characteristics were obtained from a simulated radar detection experiment. The case of the inattentive operator is selected to illustrate the effect that degradation of operator detection performance has upon radar detection. Degradations occur under nonideal conditions (example, long watch times). For the study, a degradation factor of 10 is used; this is only an arbitrary value chosen for illustrative purposes.

Detection performance was calculated for a searching operation where the radar aircraft flies in a straight track over a stationary target. Performance was given in terms of lateral range probability of detection versus lateral range. Two cases of target exposure are considered: (1) target exposed for full track of aircraft, and (2) limited target exposure with a constant probability of exposure along any portion of the track. Limited target exposure was considered as a means of introducing more realism into the detection model. Both snorkeling and surfaced submarines were considered as targets. The effect of aircraft speed on airborne ASW detection was also analyzed.

10.3 Operational Performance

Figure 232 displays lateral range detection probability vs. lateral range for search operations. At the closer lateral ranges (0 to 10 nautical miles), good detection probabilities are obtained. The curves give a decrease in detection probability with increased range, decrease in altitude, and high sea states.

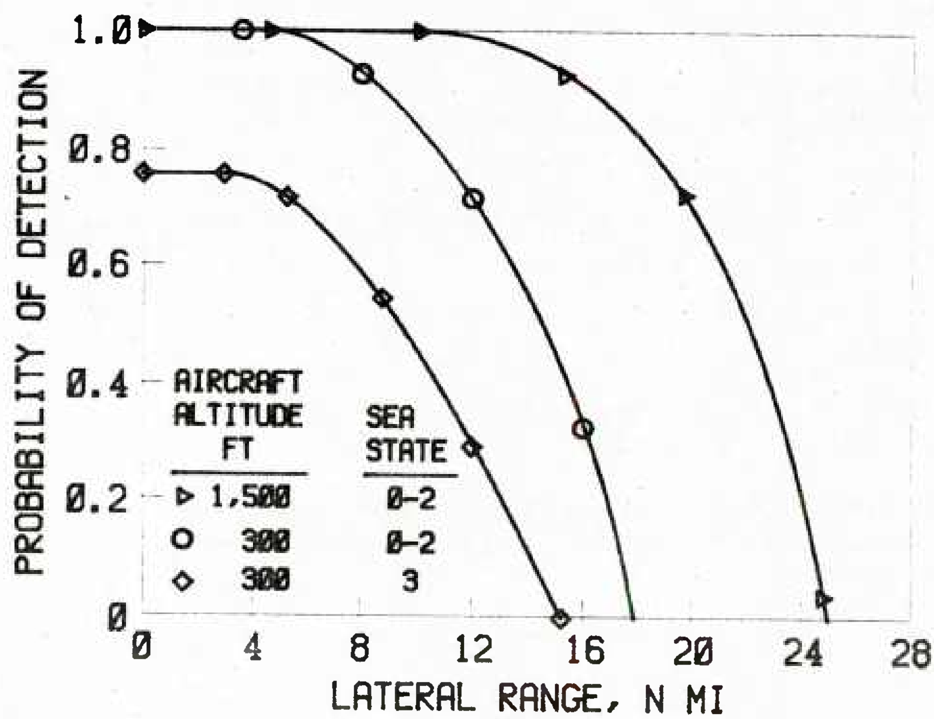


Figure 232. Lateral range probability of detection versus lateral range for the AN/APS-88 radar against a snorkeling submarine.

In contrast, Table 67 is a summary of airborne radar detection performance for carrier-based and land-based patrol aircraft against snorkeling and surfaced submarines. The performance of the APS 88 as a function of range is given in Tables 68 and 69. For comparison, the detection performance of a more powerful radar, the AN/APS-20, is summarized in Table 70. The detection performances presented in Tables 68, 69, and 70 are low and do not consider radar type, target, range, and sea state, which are meaningless when performance is at an efficiency of 10 percent or less.

Table 67

Airborne ASW Radar Detection Summary from ASW Free-play Exercises

Submarine Target	Aircraft	Radar	Assessment Range[a] (nautical miles)	Valid Detections	Missed Opportunities	Fraction Detected
Snorkeling	Search	APS-38/88	20	10	240	.04
	Patrol	APS-20/80	20	19	268	.07
Surfaced	Search	APS-38/88	30	3	46	.06
	Patrol	APS-20/80	40	8	60	.12

[a]Arbitrary selection of a reasonable maximum radar range.

Table 68

Detection Performance Summary for the AN/APS-88 Radar

Submarine target	Radar state	Targets	Range[a] (nautical miles) 0-10	10-20	20-30	30-40	40-50	50+	Total 0-20	Total 0-50+
Surfaced or broached	On	Opportunities	8	10	6	6	6	1	18	37
	Standby	Opportunities	0	1	0	0	0	0	1	1
	Inoperative	Opportunities	0	0	0	0	0	0	0	0
	On	Valid contacts	0	2	0	0	1	0	2 (11%)[b]	3 (8.1%)[b]
Snorkeling (with snorkel or ECM mast exposed)	On	Opportunities	115	95	51	43	0	0	208	302
	Standby	Opportunities	21	19	16	8	0	0	40	64
	Inoperative	Opportunities	4	3	0	0	0	0	7	7
	On	Valid contacts	8	1	0	0	0	0	9 (4.3%)[b]	9 (3.0%)[b]
False contacts		False contacts	85	78	23	4	1	2	163	193

[a]At detection or closest approach.

[b]Percentage of opportunities with radar on.

Table 69

Effect of Sea State on the Detection Performance of the ANS/APS-88 Radar

		Range (nautical miles)				
					Total	
Sea State	Targets[a]	0-10	10-20	20-30	0-20	0-30
0-1	Opportunities	44	25	7	69	76
	Valid contacts	5(11.4%)[b]	1(4%)[b]	0	6 (8.7%)[b]	6 (7.9%)[b]
	False contacts	22	20	1	42	43
2-3	Opportunities	69	63	41	132	173
	Valid contacts	3(4.4%)[b]	0	0	3 (2.3%)[b]	3 (1.7%)[b]
	False contacts	56	53	21	109	130

[a]Snorkeling submarines.

[b]Percentage of opportunities detected.

Table 70

Detection Performance of AN/APS-20 Radar Against Snorkeling Submarines

		Range (nautical miles)					
						Total	
Sea State	Targets[a]	0-10	10-20	20-30	30-40	0-20	0-30
0-1	Opportunities	34	59	35	12	93	140
	Valid contacts	3	4	1	0	7 (7.5%)[a]	8 (5.7%)[a]
	False contacts	8	9	5	6	17	28
2-3	Opportunities	51	50	17	20	101	138
	Valid contacts	6	5	2	2	11 (11%)[a]	15 (11%)[a]
	False contacts	30	47	10	19	77	106
4+	Opportunities	14	6	2	3	20	25
	Valid contacts	0	0	0	0	0 (0%)[a]	0 (0%)[a]
	False contacts	5	4	4	2	9	15

[a]Percentage of opportunities detected.

One cannot blame sea clutter effects as the major cause of the poor performance when, as shown in Tables 69 and 70, the detection performances under very low sea states (0-1) are also low. Under these conditions, the sea return or clutter effects should be relatively low compared to the higher sea states.

A note of caution must be introduced about these operational data; the targets listed as opportunities are not necessarily always realistic target opportunities. Many are outside of reasonable detection ranges for some of the conditions. Also, for the computation of sweep widths, the data are inadequate because it is not known how long each target was exposed.

A comparison of some theoretical Operational Test and Evaluation Force (OpTEvFor) results with those from the operational exercises is given in Figure 233 in terms of lateral range detection probability vs. lateral range. There is a large discrepancy between the results; the results from the free-play exercises are much lower than those obtained from the OpTEvFor evaluation. The OpTEvFor results were obtained under ideal conditions that are not representative of operational conditions because of the following factors:

a. The radar operators were in a highly attentive state; that is, they were expecting a target to appear at any time. For ASW operations, the frequency of actual targets was very low, which probably caused operators to be at less than maximum attentiveness.

b. The equipment was at a very high level of maintenance and calibration.

c. Targets are exposed for an entire track in the experiments to obtain lateral range detection probabilities vs. lateral range.

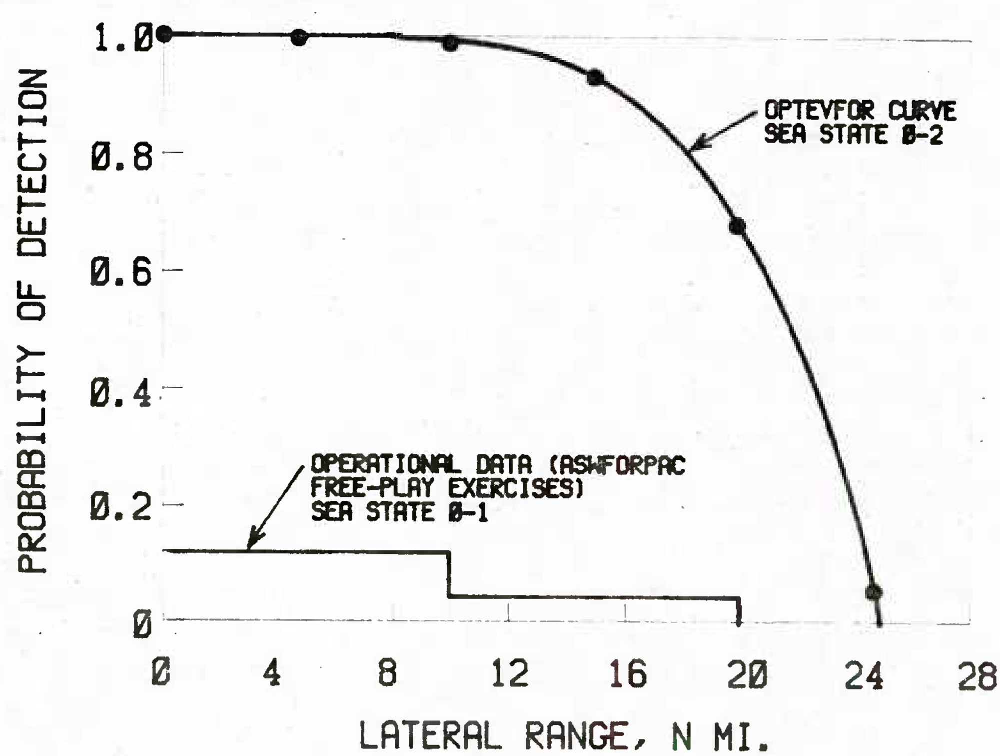


Figure 233. Lateral range detection probability vs. lateral range for the AN/APS-88 airborne radar against a snorkeling submarine. The aircraft is at 1,500 feet.

The detection performance of the radar operator in airborne ASW surveillance radars must be considered a very critical part of the overall system's performance. That is because it cannot be assumed that detection will occur whenever a preset threshold signal-to-noise ratio is exceeded for the following reasons:

a. The single-scan probability of an operator detecting a blip on a complex radar display under ideal conditions is not 1; is usually much lower. The actual value is a strong function of the signal strength or blip size.

b. Degradation in detection performance occurs when an operator is searching a radar display for long periods of time under conditions where the signal occurs irregularly and with a low frequency (vigilance conditions).

10.4 The Operator Factor

The operator factor is the probability that an operator will detect a blip when one is present. This probability is a strong function of the blip strength (directly related to target echo signal-to-noise ratio) and the psychological state of the operator. Single-scan-detection probability as a function of signal-to-noise ratio is dependent on the operator's state of attentiveness and alertness. Alertness is used in the context of knowing in what part of the scope the target will appear; this knowledge greatly reduces the area to be searched. The quality of attentiveness refers to the degree to which the operator concentrates on his search; various factors such as fatigue and boredom reduce an operator's attentiveness. A schematic representation of an operator model is given in Figure 234 in terms of detection probability vs. signal-to-noise ratio for the following three cases of attentiveness and alertness:

a. Attentive and alerted operator.
b. Attentive but unalerted operator.
c. Unattentive and unalerted operator.

In each case, the detection probability increases as signal-to-noise ratio increases. With the alerted operator, the threshold is lower than for the unalerted one. For the unattentive operator, the detection probability is less than that obtained with an attentive operator; the unattentive operator is not effectively searching the scope all of the time.

The detection difference between unalerted and alerted operators is due to the characteristics of the human eye and the reduced search area for the alerted operator. With a smaller area to be searched, an alerted operator can use the portion of his eye that has greater sensitivity to radar blips (the fovea) for more of the search than the unalerted operator can. This enables the alerted operator to detect a weak target sooner than the unalerted operator; or on a single scan, he has a higher detection probability.

The experimental curve of single-scan blip detection vs. signal-to-noise ratio given in Figure 235 shows a very strong dependence of detection probability on the signal-to-noise ratio.

Another factor that can contribute to low system performance for radar is the degradation in operator performance due to vigilance effects. Vigilance means the behavior of watching for and responding to critical signals, when these signals usually occur irregularly over relatively long periods of time. Under most vigilance conditions, there is a degradation in operator performance with watch time. A good example of this effect is given in Figure 236, where the percentage of submarine contacts and watches is

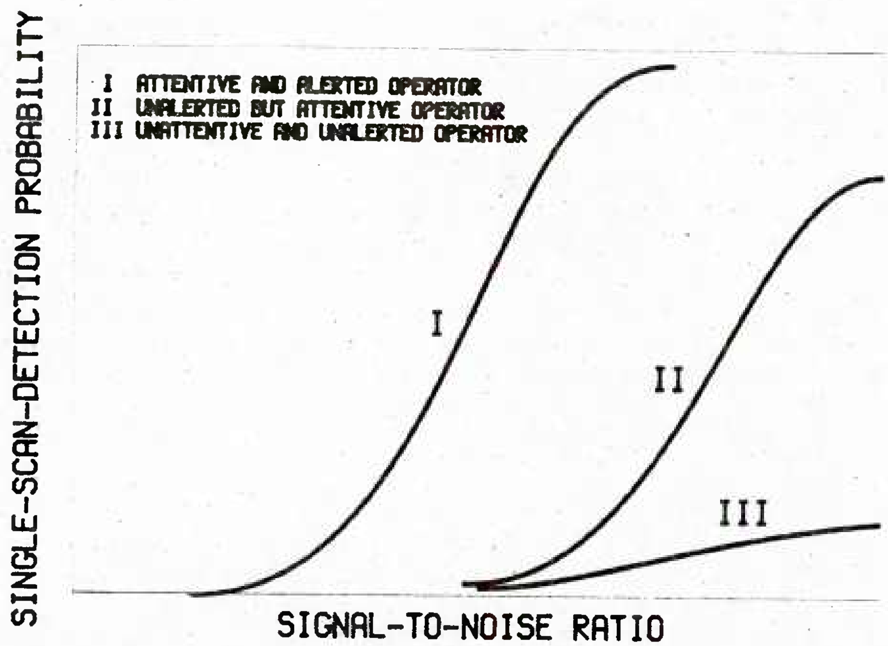


Figure 234. Single-scan probability of detection vs. signal-to-noise ratio for different operator conditions.

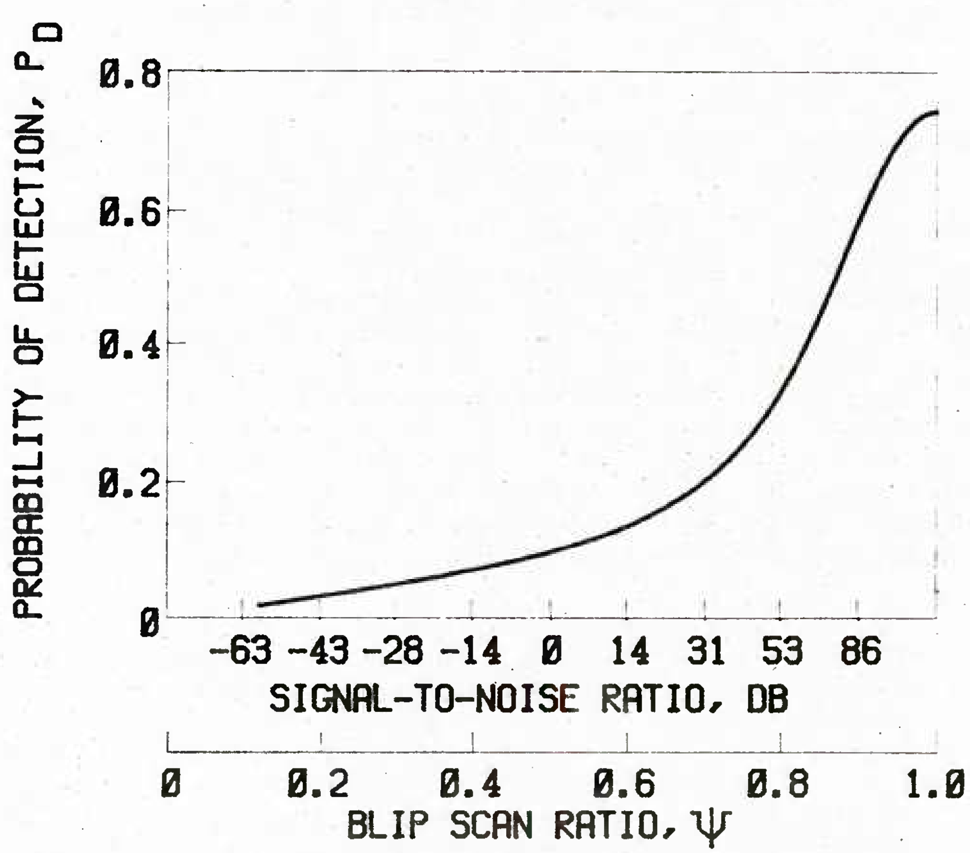


Figure 235. Detection probability vs. signal-to-noise ratio and blip-scan ratio for attentive operators. Signal-to-noise ratios referenced to value at ψ = 0.5. The target is a fluctuating signal with Rayleigh power distribution.

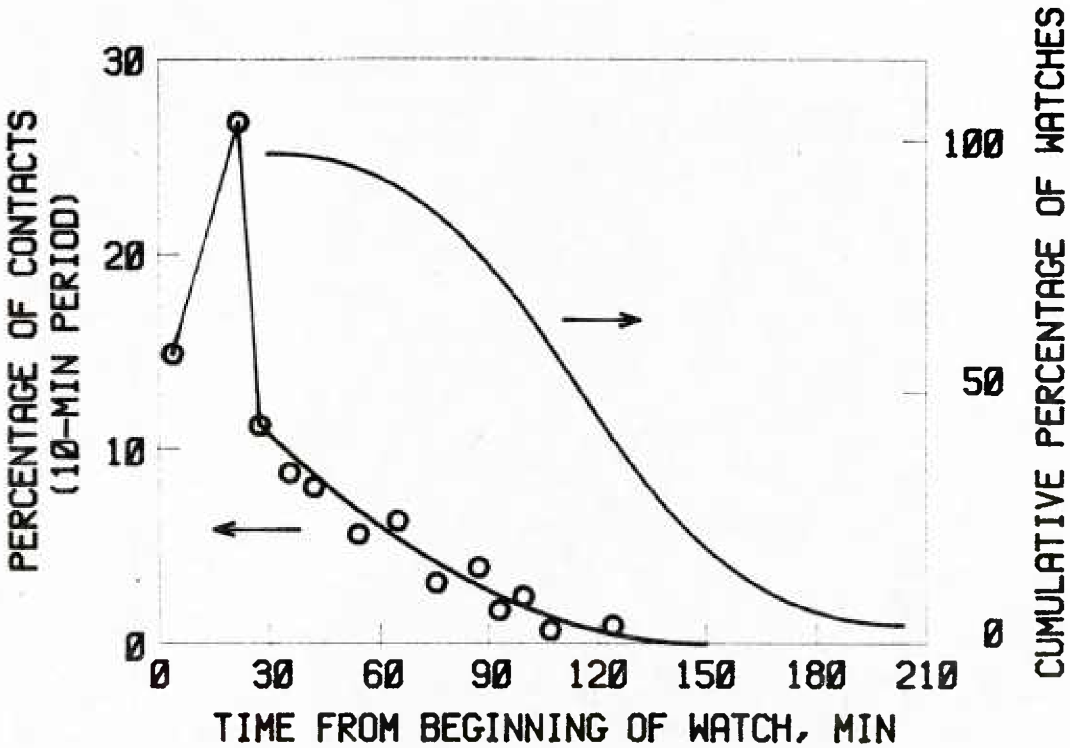


Figure 236. Cumulative percentages of lengths of watches and percentages of submarine contacts as a function of time on radar watch.

shown as a function of time from the beginning of watch. This information is used to obtain a measure of the operator's detection performance vs. time on watch by dividing the percentage of contacts by the percentage of watches. The result, a normalized detection rate per unit watch time as a function of the time on watch, is presented in Figure 237. The results show a very large fall-off in detection performance with time on watch. After about 2 hours on watch, the rate of contact detections is only about one-fifth that obtained in the first 30 minutes. This result has very serious implications for airborne radar because of the long flight times (up to 9 hours).

Based on blip-scan theory and information about the radar and the operator's performance characteristics, it is possible to calculate detection probabilities for a particular radar-target situation. These lead to the curves shown in Figure 238 where the target is exposed for the full track of the search aircraft and for a limited time.

The effect of limited target exposure on detection probability vs. lateral range is shown in Figure 239 for a 1.38 minute exposure (corresponding to a track length of 3 nautical miles for the aircraft). The number of scans on the target (8.3) is a critical value, because it is so small the operator's performance also becomes critical.

The operator's performance becomes more critical as target exposure is reduced, because low operator performance necessitates a large number of scans to detect a target; but, for short target exposure, a large number of scans is not available.

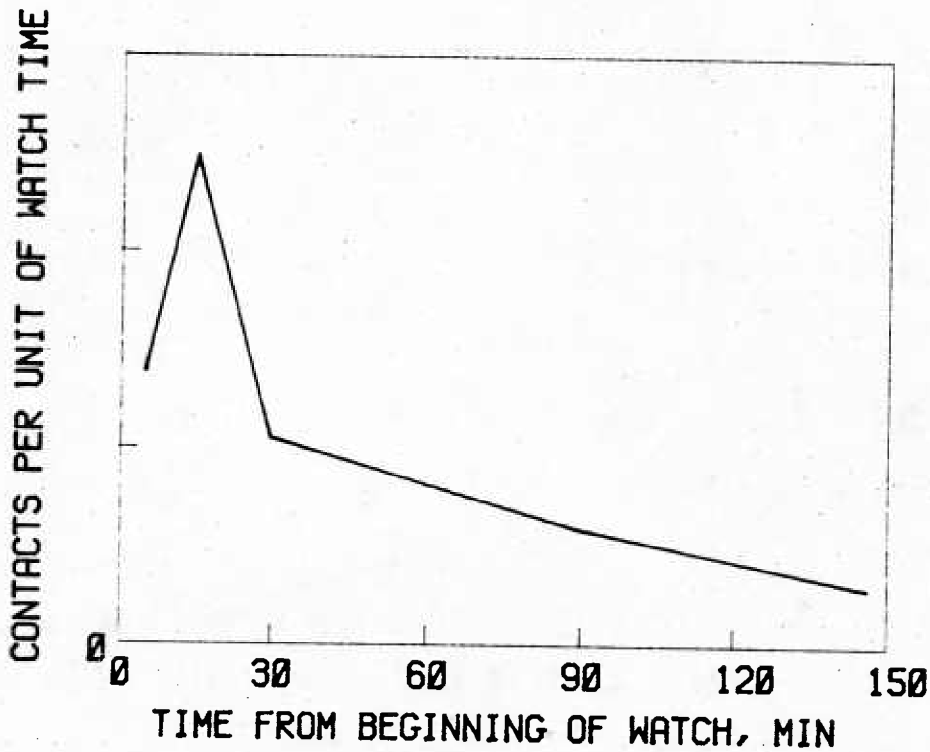


Figure 237. Effect of time on watch on the airborne radar detection of submarines.

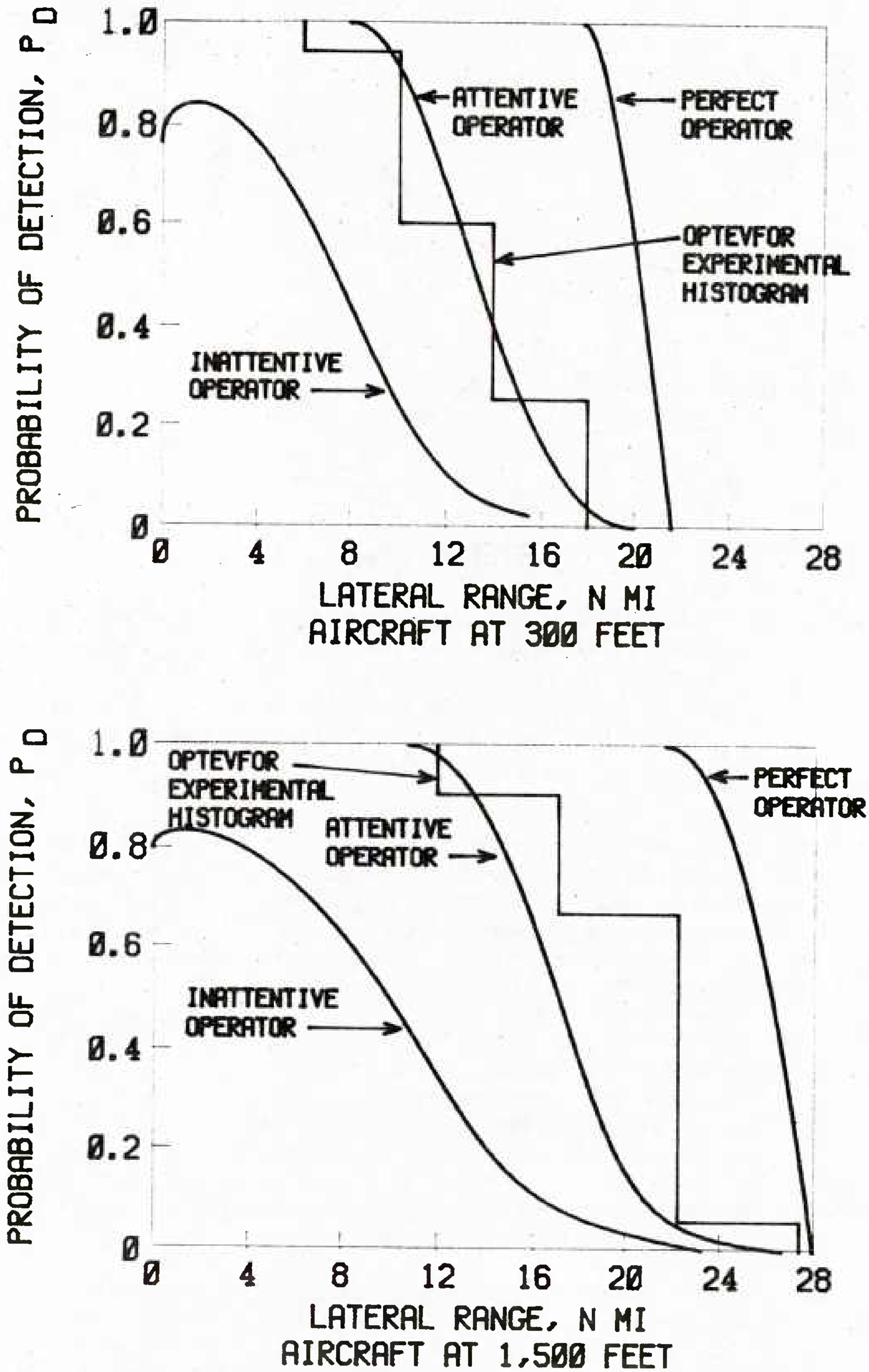


Figure 238. Lateral range detection probability vs. lateral range for different operator characteristics with the AN/APS-88 radar against snorkeling submarines. Sea state 0 to 2; target exposure, full aircraft track.

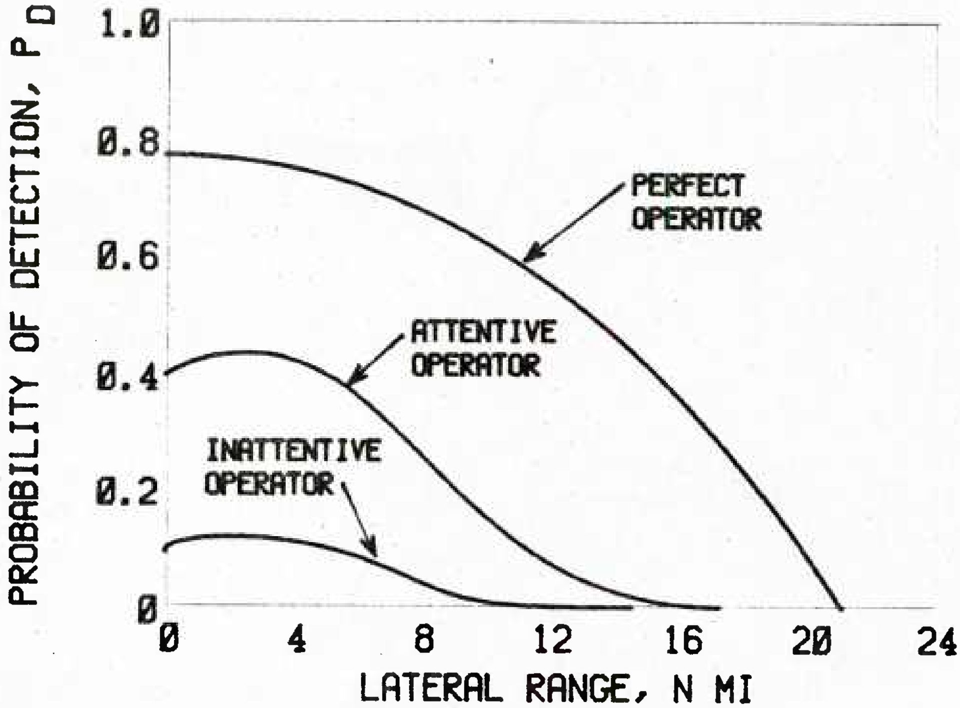


Figure 239. Effect of limited target exposure on lateral range detection probability vs. lateral range with different operator characteristics for the AN/APS-88 radar against snorkeling submarines. Sea state 0 to 2; target exposure limited to 1.38 minutes; aircraft altitude, 300 feet.

The effect of limited target exposure is shown in Figure 240 for a surfaced submarine target. The lateral range detection probability vs. lateral range is calculated for 2.3-minute exposures (5 nautical-mile tracking distance). The targets are assumed to appear with equal probability at any point on the track. As was the result with snorkeling submarines, the sensitivity of detection to operator performance is greatly increased for shortened target exposure.

Changes in sea state also influence detection probability. The calculated detection probabilities for low and high sea states are given in Table 71. The results show that detection performance under high sea state conditions can easily deteriorate to almost nothing. For realistic operator performances, attentive and inattentive, the detection performance in sea states 3 to 4 is reduced from the performance achieved in low sea states (0 to 2) by a factor of from 5 to 20. Because detection performance is already relatively low for ideal conditions (attentive operator), under high sea states the operator becomes even more important and critical.

In summary, the operator's performance can be significant and critical for many of the situations encountered in airborne ASW search and presumably also for surface radar situations. The large amount of uncertainty present in detection performance arises because of wide variations in operator performance levels. The operator's performance becomes especially critical when it is at a degraded state (inattentive) and this constitutes a serious problem because these degraded states seem to be caused by normally occurring operational conditions.

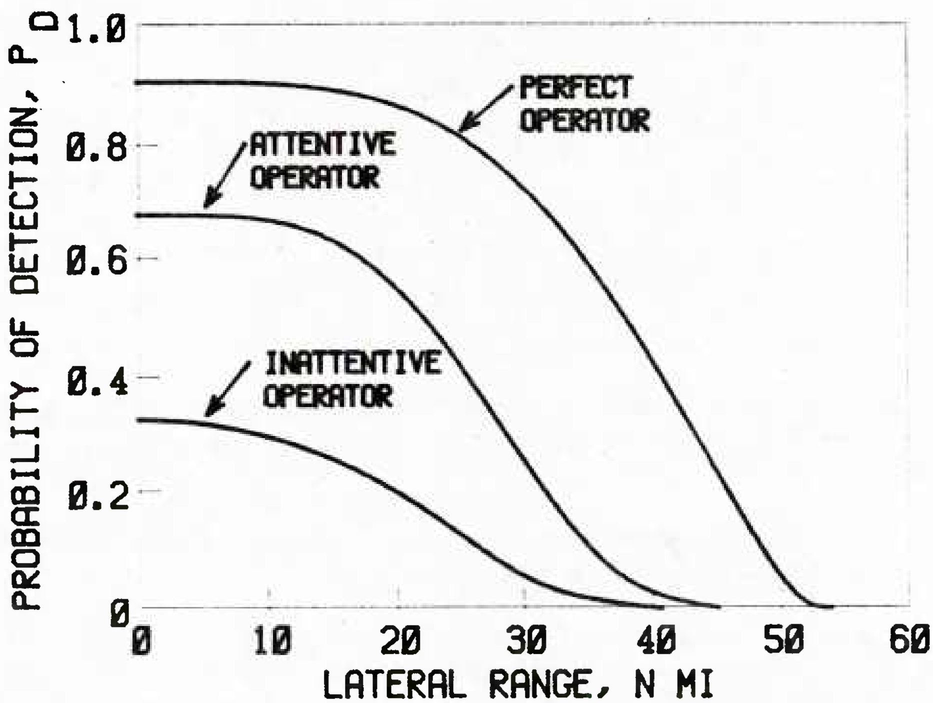


Figure 240. Effect of limited target exposure on lateral range detection probability vs. lateral range with different operator characteristics for the AN/APS-88 radar against submarines. Sea state 0 to 2; target exposure limited to 2.3 minutes; aircraft altitude, 1,500 feet.

Table 71

Estimated Detection Probabilities for Sea States 3 to 4 and 0 to 2 Against Snorkeling Submarines

Target exposure	Operator	Average detection probability (lateral range 0-10 nautical miles)	
		Sea states 3-4	Sea states 0-2
Full track	Perfect	1.00	1.00
	Attentive	0.23	0.99
	Inattentive	0.03	0.61
3 nautical mile (1.38 min)	Perfect	0.37	0.74
	Attentive	0.025	0.33
	Inattentive	0.003	0.065

10.5 A Review of the Vigilance Literature

The following is taken from Madison (1974). Teichner (1972) analyzed the vigilance literature published between 1950 and 1971 and extracted methodological information and actual data. Based on his analysis, three major factors appear to influence the probability of detecting a visual signal as a function of time of watch:

a. The initial percentage of probability of detection (i.e., the normal or pre-test level).

b. The duration of the watch.

c. Whether or not the signal-eye relationship is static or dynamic (i.e., it produces or demands continuing changes in state or position of the eye (dynamic) or does not (static)).

He located only two acceptable data sets using radar simulation and in neither case was there a decrement in performance with time.

Figure 241 is a family of curves obtained by superimposing plots of performance vs. time for experiments with different ranges of initial detection probabilities. There are some important similarities among the curves. First, the maximum decrement is fairly small in all cases. Although some of the curves appear to have the same asymptotes, the general impression is of a family of negatively accelerated, decreasing functions. Secondly, no decrement is suggested for the 30 to 39 percent interval. Where the task provides only a small initial probability of detection, there appears to be no "time on watch" effect. It is this latter type of low probability environment that shipboard watchstanders frequently encounter. This fact suggests that we should not be preoccupied with providing relief for such watchstanders every 30 minutes, when there are more significant human factors that should be occupying our attention.

This is not to say that, during periods of sonar contact prosecution, fire control engagement, or multiple target radar tracking, 30 minute breaks offer no advantage. A possible interpretation of Figure 241 is that a high initial percent detection corresponds to a fairly boring task--the operator must respond to something that is easily sensed or observed. This type of task is most sensitive to a performance decrement with time. The more challenging task, the one where there is a smaller probability of detection, seems less sensitive to the time decrement.

Some of the more significant experimental findings related to the sonar anti-submarine warfare (ASW) operations are listed below. They are from Baker and Harabedian (1962) and based on experiments with actual sonar operators and shipboard signal generating and processing equipment.

a. In a situation in which virtually all targets were detectable and the operators knew when and where to look, about 13 percent fewer targets were detected when a target was known to be imminent, but searching was required.

b. In a watchstanding situation lasting 45 minutes in which the operators did not know when nor where a target would appear, operators detected some 20 percent fewer targets than they did when they knew that a target would appear imminently.

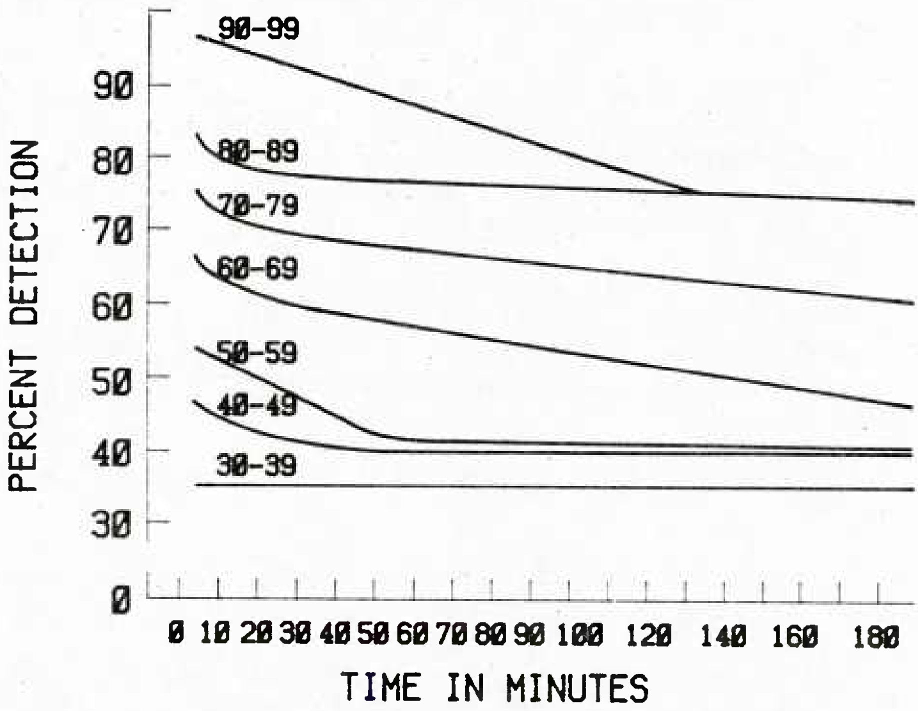


Figure 241. Percent detections vs. time on watch for various initial detection probabilities (Teichner, 1972).

c. When, at the end of a watchstanding session lasting 45 minutes, the operators were again alerted to the imminent appearance of targets, the efficiency with which they detected subsequent targets improved, but not to the same level as just prior to the watchstanding session; some "fatigue" was inferred.

d. The decrement in detection performance during watchstanding sessions occurred and was complete within the first few minutes on watch.

e. Efficiency of detection performance under conditions in which the operators were alerted to the imminent appearance of a target was moderately indicative of that during a watchstanding session lasting 45 minutes.

f. With respect to consistency of target detection performance, operators performed rather consistently within a watch, but not from one day to the next or from one experimental condition to the other. However, the frequency with which they made false reports of targets was consistent from day to day and condition to condition.

g. Efficiency of detection performance was found to be related not to target bearing, but to target range. Detection efficiency was superior for targets located near half-radius on the visual display.

h. Efficiency in the detection of sonar targets was found not to be related to criteria of ASW school achievement or scores on selected aptitude tests.

Mackie and Harabedian (1964) summarized the results of six years of research on human factor problems in ASW:

a. An average vigilance decrement (loss) of about 20 percent occurs in the first few minutes of a sonar watch. The less frequently signals appear during the watch, the more severe is the total vigilance decrement; when signal rates on a visual display are low, a variety of auditory stimuli reduces the vigilance decrement. The audio decrement appears to be less over time than does the visual decrement.

b. The introduction of artificial signals increases the probability of detecting infrequent real signals. The level of vigilance maintained by the operator is also a function of environmental stimulation from sources other than the detection displays. If the extra stimulation is not actually distracting, the added "arousal" it provides serves to facilitate vigilance.

c. Immediate knowledge of how well he is doing reduces the operator's vigilance decrement.

d. Operators expecting long intervals between signals are particularly prone to missing signals that occur soon after one that has been detected.

e. Relatively speaking, vigilance decrements are less severe in complex monitoring situations than in simple ones, although the absolute level of performance may be lower for the complex display.

f. Detection performance on redundant auditory and visual displays is superior to that on either display used alone. Operators monitoring more than one display are inclined to attend selectively to the display having the more easily recognizable signals. If the displays are not redundant, this can adversely affect detection probability.

Baker (1963) investigated sonar operator settings of bias and gain, and found that "sonar operators do not operate their displays at optimum values of bias and gain. Operation at optimum values of bias and gain should result in substantial improvements in detection performance." He recommended several practical methods for setting optimum values. One method involved making a visual threshold determination of CRT brightness through an optical filter (described in paragraph 10.6). The second involved the use of the installed sonar test set and recommended making adjustments to maximize target thresholds. (A third method, which may be applicable in some cases, involves the use of a voltmeter to set optimum values as determined from correction factors to be applied as the CRT ages.)

The following procedure, from Baker (1962), while applicable to a specific radar equipment, illustrates quite well the care that must be taken to obtain optimum noise and bias (brightness) levels in an operational environment. It may be obvious why the less effective but simpler visual reference setting has so many proponents.

10.6 Demonstrating Optimum Scope Brightness

The phenomenon of optimum scope brightness is simple to demonstrate in any setting where a pip is just visible on a scope of optimum brightness. By simply rotating the brilliance control to achieve a darker scope, the pip will disappear and then reappear when the optimum brightness is reinstated.

One manual of operational radar procedures states, under Adjustment of Controls, that "the PPI should be adjusted to the most sensitive setting for detection at maximum range." Apparently this adjustment is a matter of operator opinion and it is simple to demonstrate that there are as many opinions as there are operators. Williams and King (1946) cite operator instructions that are quite specific, but are wrong: "Adjust intensity until the sweep trace is just visible on the scope, when the IF gain is set at minimum."

What is needed is a technique for setting optimum brightness that (a) is accurate, (b) results in the same settings being made over long periods of time by the same operator, (c) results in the same setting being made by different operators, and (d) is simple to use. Obviously one could employ a voltmeter, if one knew the grid voltage appropriate for each individual CRT and how it changes with age. A photometer might be used if the correct brightness values were known. One might also use a target generator to generate a standard pip that was visible only when optimum scope brightness prevailed. These are not simple solutions.

An acceptable technique has been demonstrated by Machen et al. (1956). The human eye is not a reliable device for estimating absolute brightness, but it is remarkably precise for making threshold judgments. Advantage is taken of this fact by placing a 4-inch square glass filter of neutral density over a portion of the scope and having operators adjust scope brightness until the sweep-line is just visible through the filter. This they can do within ± .5 volt of grid bias. The filter is then removed and the scope is at optimum brightness. The theoretical density for such a filter is 3.15. For practical purposes, any filter having a density from 3.0 to 3.3 is adequate. These characteristics for an appropriate filter were first determined for CRTs having a P7 phosphor (yellow with blue flash). It is now known (Smith, A. A., & Boyes, 1957) that the same filter density is correct for a P19 magnesium fluoride screen (red-orange). The filter technique can be used also for setting the correct noise level, as described in paragraph 10.7.

10.7 Procedure for Setting Noise and Brightness with Filters

A. A. Smith (1956) described the following detailed procedure for FPS-3 radar equipment, which was commonly employed in an early-warning role. It is not known whether modification of this procedure would be necessary for other equipment.

a. To adjust noise level.

(1) With no filter in place and with video and all other sources of noise switched off, adjust brightness until the sweep-line is just visible.

(2) Place a neutral filter (4x4 in) of density 4.0 (mounted in a convenient mask if desired) over the tube face. Turn the video on and increase the video gain until the noisy sweep-line (i.e., that portion beyond local clutter and away from permanent echoes) is just visible through the filter.

(3) Leave video gain control in this position.

b. To adjust optimal bias (always after adjusting noise level).

(1) Replace the filter above with one of density 3.0 to 3.3.

(2) With video switch off, but gain control still at the setting determined in paragraph 10.7.a adjust brightness until the noise-free sweep-line is just visible through the filter. Leave the brightness control at this setting.

(3) Remove filter and turn on the necessary operating switches.

Unless major changes in range, etc. take place, no further adjustment to the brightness or gain control should be made.

In the absence of a filter for setting the noise level, it is recommended that optimum screen brightness be set with a filter of density 3.0 with no noise. Video can then be turned on full.

10.8 Operational Tests Using Optimum Scope Brightness

Bessey and Machen (1957) performed an experiment in an operational radar station, using normal air traffic. In the bright room (illumination of 0.1 fc at the scope face), scope brightness was optimum. In the other room--the dark room--scope brightness was at visual reference. The results follow:

a. In the bright room, 19.2 percent more plots were recorded than in the dark room. The probability of this difference occurring by change is less than one in 1,000.

b. Seventy tracks 20 miles or more in length were analyzed. All 70 were recorded in the bright room. In the dark room, 3 were never recorded, 10 were recorded as one plot only, and 18 were tracked for less than 20 miles.

c. Concerning earliness of initial detection, the bright room was superior to the dark room on 50 tracks, the same on 19, and inferior on one.

d. In the bright room, targets were tracked further in 43 cases, the same distance on 26, and less on one.

e. Continuity of tracking (fewer gaps) was superior in the bright room in 13 cases, and the same in 57 cases).

f. The advantage in earliness of "early warning" was computed to average 34 miles in favor of the bright room.

Three-inch, neutral density, gelatin, square filters are available in camera stores and can be used to obtain optimal noise level and brightness adjustments in a manner similar to that described. Where the exact filter density required is not available, it is a simple matter to build the proper filter; for instance, filters of .1, .2, and 3.0 can be sandwiched, to obtain a 3.3 filter.

11.0 REFERENCES

Adler, H. E. et al. Masking of cathode ray tube displays by ambient illumination (WADC Technical Report 53-266). Wright-Patterson Air Force Base, OH: Wright Air Development Center, November 1953. (AD-306 77)

Air Force Systems Command, U. S. System safety. AFSC, DH 1-6, January 1969.

Allusi, E. A. (Ed.). Lineal inclination in encoding information symbolically on cathode ray tubes and similar displays (Report ASD-TR-61-741). Aeronautical Systems Division, Wright-Patterson Air Force Base, OH: December 1961. (AD 278 825)

Allusi, E. A., & Martin, H. B. An information analysis of verbal and motor responses to symbolic and conventional arabic numerals. Journal of Applied Psychology, 1958, 42, 79-84.

Allusi, E. A., & Muller, P. F. Rates of information transfer with seven symbolic visual codes: Motor and verbal responses (Report WADC-TR-36-226). Wright-Patterson Air Force Base, OH: Wright Air Development Center, May 1956.

Altman, M., et al. High resolution wide dynamic range display equipment (Report RADC-TR-68-391). Rome, NY: Rome Air Development Center, November 1968. (AD-394 188)

Anderson, N. S., & Fitts, P. M. Amount of information gained during brief exposure of numerals and colors. Journal of Experimental Psychology, 1958, 56, 362-369.

Baker, C. A., & Grether, W. F. Visual presentation of information (Report WADC-TR-54160). Wright-Patterson Air Force Base, OH: Wright Air Development Center, 1954. (AD-43064)

Baker, C. H. Improvement in sonar operator detection performance consequent to the use of optimum bias and gain (Report HFR-TR-206-2). Goleta, CA: Human Factors Research, Inc., February 1963. (AD-403 029)

Baker, C. H. Man and radar displays (AGARD publication). London: Pergamon Press, 1962.

Baker, C. H. Factors affecting radar operator efficiency. Journal of the Institute of Navigation, Vol. XIII, 2, April 1960.

Baker, C. H., & Earl, W. K. Visual detection of positive versus negative pips on a radar PPI (Report HFR-TM-750-1). Goleta, CA: Human Factors Research, Inc., February 1968. (AD-666 577)

Baker, C. H., & Harabedian, A. A study of target detection by sonar operators (Tecnhical Report 206-16). Goleta, CA: Human Factors Research, Inc., June 1962.

Baker, C. H., & Nicholson, R. Raster scan parameters and target identification. Proceedings of the 19th Annual National Aerospace Electronics Conference, May 1967, 285-290.

Baker, C. H., & Thornton, G. B. Guide to factors affecting radar operator's efficiency. Toronto, Canada: Defense Research Medical Laboratories, December 1957. (AD-491 417)

Banks, W. W., Gertman, D. I., & Petersen, R. J. Human engineering design considerations for cathode ray tube-generated displays (Report NUREG/CR-2496, EGG-2161). Idaho Falls, ID: EG&G Idaho, Inc., April 1982.

Barmack, J. E. et al. Human factors problems in computer-generated graphic displays (Report S-234). Washington, DC: Institute for Defense Analysis, April 1966. (AD-636 170)

Bartlett, N. P., & Williams, S. B. Signal mark size and visibility of radar signals on a plan-position indicator (Systems Research Report 166-1-30). Washington, DC: Office of Naval Research, 1947.

Bessey, E. G., & Machen, G. S. An operational test of laboratory determined optima of screen brightness and ambient illumination for radar reporting rooms. Journal of Applied Psychology, 1957, 41, 51-52.

Bishop, H. P., & Crook, M. N. Absolute identification of color for targets presented against white and colored backgrounds (Report WADD TR 60-611). Wright-Patterson Air Force Base, OH: Wright Air Development Division, March 1961.

Blackwell, H. R. Contrast thresholds of the human eye. Journal Optical Society of America, 1946, 36, 624-643.

Blackwell, H. R. The effects of target size and shape on visual detection (3144-355-T). Willow Run, MI: University of Michigan, Willow Run Laboratories, February 1959. (AD-212 141)

Blackwell, H. R., Ohmart, J. G., & Brainard, R. W. Experimental evaluation of optical enhancement of literal visual displays (ASD Technical Report 61-568). Columbus, OH: Ohio State University, October 1961.

Blanchard, R. E. Survey of Navy user needs for human reliability models and data (Report 102-1). Santa Monica, CA: Behavior Metrics, December 1972. (AD-908 443L)

Bogatov, G. B. Television transmissions from outer space (Report FTD-MT-24-229-67). Wright-Patterson Air Force Base, OH: Foreign Technology Division, 1966. (AD-677 518)

Botha, B., & Shurtleff, D. Studies of display symbol legibility. Part II. The effects of the ratio of width of inactive to active elements within a TV scanline and the scan pattern used in symbol construction (Report ESD-TDR-63-440). Hanscom Field, MA: Electronic Systems Division, September 1963. (AD-420 010)

Brainard, R. W., & Caum, K. B. Evaluation of an image quality enhancement technique (Report AMRL-TR-65-143). Wright-Patterson Air Force Base, OH: Aerospace Medical Research Laboratories, September 1965. (AD-624 470)

Brainard, R. W., Hanford, E. C., & Marshall, R. H. Resolution requirements for identification of targets in television imagery (Report NA63H-794). Columbus, OH: North American Aviation, Inc., January 1965.

British Royal Navy. Human factors for designers of naval equipment (Vol. II, Chapters VI and VII). London, England: HMRN, 1971.

Bruns, R. A. Operator requirements for airborne television displays. Paper presented at the Second Annual Psychology in the Air Force Symposium, United States Air Force Academy, Colorado, April 1971.

Bruns, R. A., Bittner, A. C., Jr., & Stevenson, R. C. Effects of target size, target contrast, viewing distance and scan line orientation of dynamic televisual target detection and identification (Technical Publication TP-72-24). Point Mugu, CA: Naval Missile Center, June 1972. (AD-747 983).

Bruns, R. A., & Miller, P. L. Light transmission characteristics of three wire mesh filters for radar displays (Report NAVMISCEN TP-69-24). Point Mugu, CA: Naval Missile Center, May 1969.

Bruns, R. A., Wherry, R. J., & Bittner, A. C., Jr. Dynamic target identification on television as a function of display size, viewing distance and target motion rate (Technical Publication TP-70-60). Point Mugu, CA: Naval Missile Center, November 1970.

Bryden, J. E. Design considerations for computer driven CRT displays. Computer Design, 38-46, March 1969.

Bryden, J. E. et al. Performance of phosphors used in CRT displays. Lexington, MA: Raytheon Company, September 1965.

Buckler, A. T. A review of the literature on the legibility of alphanumerics on electronic displays (Technical Memorandum 16-77). Aberdeen Proving Ground, MD: Army Human Engineering Laboratory, May 1977.

Burg, A. Visual acuity as measured by static and dynamic tests: A comparative evaluation. Journal of Applied Psychology, 1966, 50, 460-466.

Cakir, A., Hart, D. J., & Stewart, T. F. M. The VDT manual. Darmstadt, Federal Republic of Germany: Inca-Fiej Research Association, 1979.

Cakir, A., Reuter, H. J., von Schmude, L., & Armbruster, A. Anpassung von Bildschirmarbeitsplatzen and die Physische and Funktonseise des Menschen. Berlin, Germany: Technical University, April 1978.

Carel, W. L. Pictorial displays for flight (Contract NONR-4468 (00)). Washington, DC: Office of Naval Research, December 1965. (AD-637 669).

Carel, W. L., Herman, J. A., & Hershberger, M. L. Research studies for the development of design criteria for sensor display systems. Hughes Aircraft Company Technical Report, March 1976.

Carter, R. L. LLLTV evaluation results (Report IL 704-207-62). Columbus, OH: North American Aviation, Inc., June 1962.

Chapanis, A. Some aspects of operator performance on the VJ remote radar indicator (SDC Report 166-1-91). Washington, DC: Systems Research, Office of Naval Research, 1949.

Chodil, G. Gas discharge displays for flat-panel. Proceedings of the Society for Information Display, 1976, 17, 14-22.

Christ, R. E., & Teichner, W. H. Technical report (ONR Contract N000014-70-A-0147-003). Las Cruces, NM: New Mexico State University, 1974.

Christ, R. E., & Teichner, W. H. Color research for visual displays (JANAIR Report 730703). Las Cruces, NM: New Mexico State University, 1973.

Christner, C. A., & Ray, H. W. An evaluation of the effect of selected combinations of target and background coding on map-reading performance. VI. Human Factors, 1961, 3, 131-146.

Clarke, A. A. Opto-electronic systems: Perceptual limitations and display enhancement. AGARD Lecture Series 76 in Electro-optical System Advisory Group for Aerospace Research and Development, Neuilly sur Seine, France, May 1975, 5-1 through 5-12.

Clauer, C. L. Legibility analysis of television systems (Laboratory report 16.158). Los Gatos, CA: IBM, 1967.

Cobb, P. W., & Moss, F. K. The four variables in the visual threshold. Franklin Institute Journal, 1928, 205, 831-847.

Colman, K. W., Courtney, D., Freeman, J. B., & Bernstein, R. The control of specular reflections from bright tube radar displays (Courtney and Company Report No. 23). Washington, DC: Office of Naval Research, November 1958. (AD-209 279)

Collier, R. M. An experimental study of form perception in indirect vision. Journal of Comparative Psychology, 1931, 11, 281-290.

Connolly, D. W., Spanier, G., & Champion, F. Color display evaluation for air traffic control (Report FAA-RD-75-39). Washington, DC: Federal Aviation Administration, May 1975.

Cook, T. C. Color coding--a review of the literature (HEL Technical Note 9-74). Aberdeen Proving Ground, MD: Army Human Engineering Laboratory, November 1974.

Cornsweet, T. N. Visual perception. New York: Academic Press, 1970.

Craik, K. J. W., & Macpherson, S. J. The effect of certain operating conditions on the visibility of PPI radar echoes (Report APU 16145). London, England: Medical Research Council, 1945.

Crawford, B. H. Visibility of the trace on PPI tubes (Refs. Phot. 479-1-79). Teddington, Middlesex, England: National Physical Laboratory, 1950.

Crisp, M. D., Hinson, D. C., & Siegel, J. I. Luminous efficiency of a Digivue display/memory panel. Proceedings of the 1974 Conference on Display Devices and Systems, 9-10 October, 1974.

Crook, M. N., Hanson, J. A., & Weisz, A. Legibility of type as a function of stroke-width, letter width, and letter spacing under low illumination (WADC Technical Report 53-440). Wright-Patterson Air Force Base, OH: Wright Air Development Center, March 1954. (a)

Crook, M. N., Hanson, J. A., & Weisz, A. Legibility of type as determined by the combined effect of typographical variables and reflectance of background (Report WADC 53-441). Wright-Patterson Air Force Base, OH: Wright Air Development Center, March 1954. (b)

Crumley, L. et al. Display problems in aerospace surveillance systems. Part I. A survey of display hardware and analysis of relevant psychological variables (Report ESD-TR-61-33). Bedford, MA: Electronics Systems Division, L. G. Hanscom Field, June 1961. (AD-263 543)

Dalisa, A. L. Electrophoretic display technology. Proceedings of the Society for Information Display, 1977, 18, 43-50.

D'Aiuto, J. R. Resolution, video bandwidth and frame time. Information Display, 1969, 6, 58-59.

Deese, J. Signal size and detectability on PPI display (Report WADC TR-54-166). Wright-Patterson Air Force Base, OH: Wright Air Development Center, August 1954. (AD-539 78)

Department of Defense. Human engineering design criteria for miliary systems, equipment and facilities (MIL-STD 1472C). Washington, DC: Author, 2 May 1981.

Dyer, W. R., & Christman, R. J. Relative influence of time, complexity, and density on utilization of coded large scale displays (Report RADC-TR-65-235). Rome, NY: Rome Air Development Center, September 1965. (AD-622 786)

Ellis, B., Burrell, G. J., Wharf, J. H., & Harokins, T. D. F. The format and color of small matrix displays for use in high ambient illumination (Technical Report 75048). Royal Aircraft Establishment, March 1975.

Engel, S. E., & Granda, R. D. Guidelines for man/display interfaces (Report TR 00.2720). Poughkeepsie, NY: International Business Machines Corporation, December 19, 1975.

Enoch, J. M. Natural tendencies in visual search of a complex display. In Visual Search Techniques, NAS-NRC Publication 712, 1960.

Ericksen, C. W. Multidimensional stimulus differences and accuracy of discrimination (WADC TR54-165). Wright-Patterson Air Force Base, OH: Wright Air Development Center, 1954.

Ericksen, C. W., & Hake, H. W. Multidimentional stimulus difference and accuracy of discrimination. Journal Experimental Psychology, 1955, 50, 153-160.

Erickson, R. A. Line criteria in target acquisition with television. Human Factors, 1978, 20, 573-588.

Erickson, R. A. Visual search performance in a moving structured field. Journal Optical Society of America, 1964, 54, 399-405.

Erickson, R. A., & Hemingway, J. C. Image identification on television (Report NWC TP 5025). China Lake, CA: Naval Weapons Center, September 1970. (AD-876 331)

Erickson, R. A., Hemingway, J. C., Craig, G. L., & Wagner, D. W. Resolution of moving imagery on television: Experiment and application (Report NWC TP 5619). China Lake, CA: Naval Weapons Center, February 1974.

Erickson, R. A., Linton, P. M., & Hemingway, J. C. Human factors experiments with television (Report NWC TP 4573). China Lake, CA: Naval Weapons Center, October 1968.

Erickson, R. A., & Main, R. E. Target acquisition on television: Preliminary experiments. China Lake, CA: Naval Ordnance Test Station, August 1966. (AD-488 320L)

Erickson, R. A., Main, R. E., & Burge, C. G. Airborne television monitor evaluation (Report NOTS-TP-4209). China Lake, CA: Naval Ordnance Test Station, 1967.

Farrell, R. J., & Booth, J. M. Design handbook for imagery interpretation equipment (Technical Report D180-19063-1). Seattle, WA: Boeing Aircraft Company, December 1975.

Faulkner, T. W., & Murphy, R. J. Lighting for difficult visual tasks. Human Factors, 1973, 15, 149-162.

Fehrer, E. V. An investigation of the learning of visually perceived forms. American Journal of Psychology, 1935, 47, 187-221.

Fowler, F. D., & Jones, D. B. Target acquisition studies: (1) translation from direct to TV mediated viewing; (2) target acquisition performance: Color vs. monochrome TV displays (Technical Report No. NR 196-071). Orlando, FL: Office of Naval Research, Martin-Marietta, OR 11,768, January 1972. (AD-736 244)

Fowler, F. D., Freitag, M., Jones, D. B., & King, B. C. Target acquisition studies: (1) two dimensional compared with three dimensional targets; (2) changes in gamma for TV displayed targets (Report OR 11,091). Orlando, FL: Martin-Marietta Company, January 1971.

Gardner, R. E., & Carl, J. M. The effects of ambient illumination, CRT bias, and noise upon target detectability with a B-display (Report 5264). Washington, DC: U.S. Naval Research Laboratory, January 1959. (AD-211 751)

Garner, W. R., & Creelman, C. G. Effect of redundancy and duration on absolute judgments of visual stimuli. Journal of Experimental Psychology, 1964, 67, 168-172.

Garner, W. R., & Hamburger, F. Detectability and discriminability of targets on a remote projection plan-position indicator. Proceedings of the Institute of Radio Engineers, 1947, 35, 1220-1225.

Gaven, J. V., Jr., Tavitian, J., & Harabedian, A. The informative value of sampled images as a function of the number of gray levels used in encoding the images. Photographic Science and Engineering, 1970, 14, 16-20.

Gerathewohl, S. J. Conspicuity of Flashing Signals of Different Frequency and Duration. Journal of Experimental Psychology, 1954, 48, 247-251.

'ings, B. J. Alphanumerics for raster displays. Ergonomics, 1972, 15, 65-72.

Goede, W. F. Flat-panel displays: Six major problems and some solutions. San Francisco: Stanford/S.I.D. Seminar, 17 April 1978.

Goede, W. F. A digitally-addressed flat panel CRT review. IEEE INTERCON, 1973, 5, 33/2.

Gorrel, E. L. A human engineering specification for legibility of alphanumeric symbology on video monitor displays (Technical Report 78746). Toronto, Canada: Defense and Civil Institute of Environmental Medicine, December 1978.

Gould, J. D. Visual factors in the design of computer-controlled CRT displays. Human Factors, 1968, 10, 359-376.

Grant, G., et al. Display problems in aerospace surveillance systems (Report ESD-TRD-61-57). Bedford, MA: HRB-Singer, Inc., October 1961. (AD-271 440)

Grant, C. R., & Ferris, W. R. Evaluation of a high-speed PPI scan (Report 3960). Washington, DC: Naval Research Laboratory, 1952.

Green, B. F., McGill, W. J., & Jenkins, H. M. The time required to search for numbers on large visual displays (Report No. 36). Lincoln Laboratory, Massachusetts Institute of Technology, August 1953.

Greening, C. P., & Wyman, M. J. The effects of dynamic range and briefing level upon target recognition with high resolution radar displays (Report X9-365/501). Anaheim, CA: Autonetics, February 1969.

Greening, C. P., & Wyman, M. J. The effects on the number of shades of gray upon target recognition with high resolution radar displays (Report T8-2038/501). Santa Monica, CA: Autonetics, September 1968.

Grether, W., & Baker, C. A. Visual presentation of information. Chapter 3 in H. P. van Cott, & R. D. Kinkade (Eds.). Human Engineering Guide to Equipment Design (2nd Ed.). Washington, DC: U.S. Government Printing Office, 1972.

Haeusing, M. Color coding of information on electronic displays. Proceedings of the Sixth Congress of the International Ergonomics Association, 1976, 210-217.

Hairfield, H. W. Night and all-weather target acquisition: State-of-the-art review. Part IV: Television sensor systems (Report D162-10116-4). Seattle, WA: Boeing Company, 1970. (AD-514 552L)

Hammer, C. H., & Ringel, S. Information assimilation from updated alpha-numeric displays. Journal of Applied Psychology, 1966, 50, 383-387.

Hanes, R. M. Some effects of shape on apparent brightness. Journal of Experimental Psychology, 1950, 40, 650-654.

Hanes, R. M., & Rhodes, M. V. Color identification as a function of extended practice. Journal of the Optical Society of America, 1959, 49, 1060-1064.

Harriman, M. W. Visibility of cathode-ray tube screens: Search time as a function of signal strength. Journal of Psychology, 1950, 29, 247-250.

Harris, C. S. et al. Human performance during vibration (Report AMRL-TR-65-204). Wright-Patterson Air Force Base, OH: Aerospace Medical Research Laboratories, November 1965. (AD-624 196)

Heglin, J. NAVSHIPS display illumination design guide, Section II: Human factors. San Diego: Naval Electronics Laboratory Center, 1973.

Helson, H., & Fehrer, E. V. The role of form in perception. American Journal of Psychology, 1932, 44, 79-102.

Hemingway, J. C., & Erickson, R. A. Relative effects of raster scan lines and image subtense on symbol legibility on television. Human Factors, 1969, 11, 331-338.

Hillman, B. Human factors in airborne television displays. Boston: National Symposium on Information Display, Society for Information Display, October 1966.

Hitt, W. D. An evaluation of five different abstract coding methods. Human Factors, 1961, 3, 120-130.

Hochberg, J. E., Gleitman, H., & Macbride, P. D. Visual threshold as a function of simplicity of form. American Psychologist, 1948, 3, 341-342.

Hoffman, C. S., & Greening, C. P. Effect of blur and size on target recognition. Aerospace Medicine, 1967, 38, 156-158.

Horowitz, P. Concepts for design and implementation of mobile computer generated display systems. 6th National Symposium on Information Display: Technical Proceedings, September 1965, 47-66.

Horton, G. P. Accuracy of reading target location and size of schematic PPI display (Technical Report 5961). United States Air Force, October 1949.

Howell, W. C. et al. Influence of stress variables on display design (Report RADC-TR-66-42). Rome, NY: Rome Air Development Center, April 1966. (AD-481 509)

Howell, W. C., & Kraft, C. L. Size, blur and contrast as variables affecting the legibility of alphanumeric symbols on radar-type displays (Technical Report 59-36). Wright-Patterson Air Force Base, OH: Wright Air Development Center, September 1959.

Hughes Aircraft Company. Research studies for the development of design criteria for sensor display systems. Culver City, CA: Author, March 1976. (AD-A023298)

Human Engineering Laboratory, Human factors engineering standard for missile systems and related equipment (HEL Standard 5-3-65). Aberdeen Proving Ground, MD: U.S. Army Human Engineering Laboratory, September 1965.

Humes, J. M., & Bauerschmidt, D. K. Low light level TV viewfinder simulation program, Phase B (Report AFAL-TR-68-271). Wright-Patterson Air Force Base, OH: Air Force Avionics Laboratory, November 1968.

Illumination Engineering Society, I.E.S. Lighting Handbook, Third Edition. Illumination Engineering Society, New York, 1959.

Ireland, F. H. Effects of surround illumination on visual performance: An annotated bibliography (Report AMRL-TR-67-103). Wright-Patterson Air Force Base, OH: Aerospace Medical Research Laboratories, July 1967. (AD-822 012)

Ireland, F. H., Kinslow, E., Levin, E., & Page, D. Experimental study of the effects of surround brightness and size on visual performance (Report AMRL-TR-67-102). Wright-Patterson Air Force Base, OH: Aerospace Medical Research Laboratories, September 1967. (AD-666 045)

JEDEC Electron Tube Council. Optical characteristics of cathode ray tube screens. Publication Number 16A, 1966.

Johnson, J. Analysis of image forming systems. In Image Intensifier Symposium. Ft. Belvoir, VA: October 6-7, 1958. (AD-220 160)

Johnston, D. M. Target recognition on TV as a function of horizontal resolution and shades of gray. Human Factors, 1968, 10, 201-210.

Jones, D. B., Freitag, M., & Collyer, S. C. Air-to-ground target acquisition source book: A review of the literature (Report OR 12,470). Orlando, FL: Martin-Marietta, September 1974.

Judd, D. B. Colorimetry (National Bureau of Standards Circular 478). Washington, DC: National Bureau of Standards, March 1950.

Kazan, B. Electroluminescent displays. Proceedings of the Society for Information Display, 1976, 17, 23-29.

Kelly, K. R. A universal color language. Color Engineering, 1965, 3(2), 1-7.

Ketchel, J. M., & Jenney, L. L. Electronic and optically generated aircraft displays: A study of standardization requirements (JANAIR report 680505). Washington, DC: Office of Naval Research, May 1968. (AD-684 849)

Kinder, F. A., Stedman, R. J., & Holt, L. J. Visual aircraft control using television techniques (VISCON system) (Report NWC-TP-5052). China Lake, CA: Naval Weapons Center, October 1970.

King, H., Landis, C., & Zubin, J. Visual subliminal perception where figure is obscured by the illumination of the ground. Journal of Experimental Psychology, 1944, 34, 60-69.

Kinney, D. G. Airborne ASW radar detection: A consideration of the operator factors for the AN/APS-88 radar under low sea state conditions (Report NWC-TR-4533). China Lake, CA: Naval Weapons Center, November 1968. (AD-394 774)

Kinney, G. C. Studies in display legibility (Report MTP-21). Cambridge, MA: MITRE Corp., December 1965.

Knowles, W. B., & Wulfeck, J. W. Visual performance with high-contrast cathode-ray tubes at high levels of ambient illumination. Human Factors, 1972, 14, 521-532.

Kober, C. L. Critical size of radar PPI cathode ray tube screens and antenna scan rate (Tech. Proceed. DU-72), June 1952. (AD-50 007)

Koffka, K. Principles of Gestalt Psychology. New York: Harcourt Brace and Company, 1935.

Krebs, M. J., Wolf, J. D., & Sandvig, J. H. Color display design guide (Report ONR-CR213-136-2F). Minneapolis, MN: Honeywell Systems and Research Center, October 1978. (AD-A066 630)

Lefford, A. Preliminary studies of detection time and other factors involved in AEW performance (SDC Report 279-3-4). Washington, DC: Office of Naval Research, Systems Research, August 1950.

Leininger, W. E., Bliss, W. D. et al. Aerial terrain orientation by means of television display (Report NMC-TM-63-39). Point Mugu, CA: Naval Missile Center, 1963.

Levine, S. H., Jauer, R. A., & Kozlowski, D. R. Human factors requirements for electronic displays: Effects of S/N ratio and TV lines over target (Report A0217). St. Louis, MO: McDonnell Douglas Corporation, January 1970. (AD-744 486)

Lindsley, D. B. Vision as related to proficiency in oscilloscope operation (Report No. 8). OSRD report 3409, Applied Psychology Panel, NDRC, 1944.

Lipschultz, H. E., & Sandberg, K. O. W. Target indication as a function of instruction (SDC Report 166-1-34). Washington, DC: Office of Naval Research, Systems Research, 1947.

Lovelace Foundation. Compendium of human responses to the aerospace environment (Vols. I-IV) (NASA CR-1205 (I-IV). Albuquerque, NM: Lovelace Foundation for Medical Education and Research, November 1968.

Luxenberg, H. R., & Bonness, Q. L. Quantitative measures of display characteristics. Information Display, July/August 1965, 8-14.

Luxenberg, H. R., & Kuehn, R. L. Display system engineering. New York: McGraw-Hill, 1968.

Machen, G. S. et al. A simple method of setting optimum scope brightness on PPIs (Report 163-6). Canada: Defense Research Board, 1956.

Mackie, P. R., & Harabedian, A. A study of simulation requirements for sonar operator trainers (Report NAVTRADEVCEN 1320-1). Pt. Washington, NY: Navy Training Device Center, 1964.

Maddox, M. I., Burnette, J. T., & Gutmann, J. C. Font comparisons for 5 x 7 dot matrix characters. Human Factors, 1977, 10, 89-93.

Madison, R. L. Human factors in destroyer operations (Thesis). Monterey, CA: Naval Postgraduate School, March 1974. (AD-775 011)

McLean M. V. Brightness contrast, color contrast, and legibility. Human Factors, 1965, 7, 521-526.

Meister, D., & Sullivan, D. J. Guide to human engineering design for visual displays (Office of Naval Research Contract No. N00014-68-C-0278). Washington, DC: Office of Naval Research, Engineering Psychology Branch, 1969. (AD-693 237)

Middleton, W. E. K. Vision through the atmosphere. Toronto, Canada: University of Toronto Press, 1952.

Miller, R. B. Response time in man-computer conversational transactions (Report TR-00.1660-1). Poughkeepsie, NY: IBM Corporation, 1968.

Moon, P., & Spencer, D. D. Visual data applied to lighting design. Journal Optical Society of America, 1944, 34, 605-617.

Morgan, C. T. Theory and problems of radar visibility: Intensity modulated scopes (Report 3965). Washington, DC: Naval Research Laboratory, 1952.

Munn, N. L., & Geil, G. M. A note on peripheral form discrimination. Journal of General Psychology, 1931, 5, 78-88.

Murrell, K. F. H. Two studies of decrement of performance with time: (i) in plotting telephoned information and (ii) in radar reporting (Report 42). British Naval Motion Study Unit, February 1951.

Myers, W. S. Accommodation effects in multicolor displays (Report AFFDL TR-67-161). Wright-Patterson Air Force Base, OH: Air Force Flight Dynamics Laboratory, December 1967. (AD-826 134)

Neal, A. S. Legibility requirements for educational television. Information display, 1968, 5, 39-44.

Newman, K. M., & Davis, A. R. Non-redundant color, brightness, and flashing rate encoding of geometric symbols on a visual display. Journal of Engineering Psychology, 1962, 1, 47-67.

Oatman, L. C. Target detection using black and white television; Study III: Detection as a function of display degradation (Report HEL-TM-12-65). Aberdeen Proving Ground, MD: U.S. Army Human Engineering Laboratory, Aberdeen Proving Ground, MD, September 1965. (AD-627 009) (a)

Oatman, L. C. Target detection using black and white television, Study II: Degraded resolution and target detection probability (Report HEL-TM-10-65). Aberdeen Proving Ground, MD: U.S. Army Human Engineering Laboratory, July 1965. (AD-625 230) (b)

Ota, I., Sato, T., Tanaka, S., Yamagami, T., & Takeda, H. Paper presented at Laser 75 Seminar, Munich, Germany, June 1975.

Ozkaptan, H. et al. Target acquisition studies: Fixed television fields of view (Report OR 9656). Orlando, FL: Martin-Marietta Corp., October 1968. (AD-677 322)

Parkes, K. R. Human factors in air-to-ground target acquisition (Dissertation). Loughborough, England: Loughborough University of Technology, April 1972.

Pollack, J. D. Reaction time to different wavelengths at various luminances. Perception and Psychophysics, 1968, 3, 17-24.

Poole, H. H. Fundamentals of display systems. New York: Spartan Books, 1966.

Reading, V. M. (Ed). Visual aspects and ergonomics of visual display units. London, England: Department of Visual Science, University of London, Institute of Opthalmology, 1978.

Rey, P., & Meyer, J. J. Problemes visuels aux ecrans de visualisation. Geneva, Switzerland: Group de Recherche sur les ecrans de visualisation. 16 December 1977.

Rizy, E. F. Dichroic filter specification for color additive displays. II. Further exploration of tolerance areas and the influence of other display variables (RADC-TR-67-513). Griffiss Air Force Base, NY: Rome Air Development Center, September 1967. (AD-659 346)

Rosell, F. A., & Willson, R. H. Recent psychophysical experiments and the display signal-to-noise ratio concept. In L. M. Biberman (Ed.). Perception of Displayed Information, New York: Plenum Press, 1973.

Rupp, B. Visual display standards. Proceedings of the Society for Information Display, 1981, 22, 1-10.

Rusis, G. Laboratory studies in air-to-ground target recognition. VIII. The effect of TV image enhancement in the observer-initiated freeze mode (Report T6-276/3111). Anaheim, CA: Autonetics, January 1966.

Rusis, G., & Snyder, H. L. The effect of TV camera field of view and size of targets upon air-to-ground target recognition. Human Factors, 1965, 7, 493-501.

Rusis, G., Snyder, H. L., & Greening, C. P. Laboratory studies in air-to-ground target recognition. IV. The effect of TV display freeze (Report T5-738/3111). Anaheim, CA: Autonetics, May 1965.

Rusis, G., Snyder, H. L., Greening, C. P., & Rawlings, S. G. Laboratory studies in air-to-ground target recognition: VII. Further research on the effect of TV display freeze (Report T5-1463/3111). Anaheim, CA: Autonetics, October 1965.

Saenz, N. E., & Riche, C. V., Jr. Shape and color as dimensions of a visual redundant code. Human Factors, 1974, 16, 306-313.

Scanlon, L. A., & Carel, W. L. Human performance evaluation of matrix displays: literature and technology review (Report AMRL-TR-76-39). Wright-Patterson Air Force Base, OH: Aerospace Medical Research Laboratory, June 1976.

Scheffer, T. J. Liquid crystal color displays. In A. R. Kmetz & F. K. von Willison (Eds.). Nonemissive electrooptic displays. New York: Plenum, 1976.

Schlam, E. Electroluminescent phosphors. Proceedings of the IEEE, 1973, 61, 894-901.

Scott, D. M. Visibility on radar screens: Centred versus offcentred operation (Report 163-7). Defence Research Board of Canada, 1957.

Seibert, W. F. The legibility of televised visuals: A study of signal bandwidth and other factors (Unpublished study). West Lafayette, IN: Purdue University, Instructional Media Research Unit, December 1964.

Seibert, W. F., Kasten, D. F., & Potter, J. R. A study of factors influencing the legibility of televised characters. Journal of Society of Motion Pictures and Television, 1959, 68, 467-472.

Self, H. C. Acquisition slant ranges for targets (Report AMRL-TR-70-96). Wright-Patterson Air Force Base, OH: Aerospace Medical Research Laboratory, May 1971.

Self, H. C. Image evaluation for the prediction of the performance of a human observer. Paper presented at the NATO Symposium on Image Evaluation, Munich, West Germany, August 1969.

Semple, C. A., Jr., Heapy, R. J., Conway, E. J., & Burnette, K. Y. Analysis of human factors data for electronic flight display systems (Report AFFDL-TR-70-174). Wright-Patterson Air Force Base, OH: Air Force Flight Dynamics Laboratory, April 1971. (AD-884 770)

Shanahan, D. Effects of television bandwidth on target identification (Report NMC-TM-64-2). Point Mugu, CA: Naval Missile Center, April 1964.

Sherr, S. Electronic displays. New York: Wiley-Interscience, 1979.

Shurtleff, D. A. How to make displays legible. La Mirada, CA: Human Interface Design, 1980.

Shurtleff, D. A. Legibility research. Proceedings of the Society for Information Display, 1974, 15, 41-51.

Shurtleff, D. A. Studies of display symbol legibility: XXII. The relative legibility of four symbol sets made with a five by seven dot matrix (Report MTR-833). Bedford, MA: The MITRE Corporation, December 1969.

Shurtleff, D. A. Studies of display symbol legibility: XXIII. The relative legibility of dot symbols formed from different matrices and the legibility of overprinted dot symbols (Report ESD-TR-69-444). Bedford, MA: Hanscom Air Force Base, February 1970. (a)

Shurtleff, D. A. Studies of display symbol legibility: XXIV. The relative legibility of special symbols formed from different dot matrices and the legibility of overprinted special symbols (Report ESD-TR-69-439). Bedford, MA: Hanscom Air Force Base, February 1970. (b)

Shurtleff, D. A. Studies of display symbol legibility: XXV. The relative legibility of stroke-generated symbols and a comparison of the legibility of stroke symbols and dot symbols (Report ESD-TR-70-203). Bedford, MA: Hanscom Air Force Base, Electronics Systems Division, June 1970. (c)

Shurtleff, D. A. Studies in television legibility--A review of the literature. Information Display, 40-45, January/February 1967.

Shurtleff, D. A. Studies of display symbol legibility: II. Factors in the legibility of television displays (Report ESD-TR-66-299). Bedford, MA: Hanscom Air Force Base, USAF Electronic Systems Division, August 1966. (a)

Shurtleff, D. A. Design problems in visual displays, part II: Factors in the legibility of televised displays (Report ESD-TR-66-299). Bedford, MA: The MITRE Corporation, September 1966. (AD-640 571) (b)

Shurtleff, D. A., & Alexander, P. J. Symbol designs for the graphic symbol subset of the ASCII (Report MTR-2456). Bedford, MA: The MITRE Corporation, September 1972.

Shurtleff, D., Marsetta, M., & Showman, D. Studies of display symbol legibility: Part IX. The effects of resolution, size and viewing angle on legibility (Technical Report ESD-TR-65-411). Bedford, MA: Hascom Field, Decision Sciences Laboratory, May 1966.

Shurtleff, D. A., & Wuersch, W. F. Legibility criteria in design and selection of data displays for group viewing. Proceedings of the Human Factors Society, Annual Meeting, November 1979.

Shurtleff, D., Botha, B., & Young, M. Studies of display symbol legibility: IV. The effects of brightness, letter spacing, symbol-background relation and surround brightness on the legibility of capital letters (Report ESD-TR-65-134). Bedford, MA: Hanscom Air Force Base, May 1966.

Shurtleff, D., Botha, B., & Young, M. Studies of display legibility: III. The effects of scan line orientation (Working Paper W-6899). Bedford, MA: The MITRE Corporation, December 1963.

Simon, C. Rapid acquisition of radar targets from moving and static displays. Human Factors, 1965, 7, 185-206.

Sinaiko, H. W., Lefford, A., & Taubman, R. E. Functional relationship of time density to the detection of discrete radar target events (SDC Report 279-3-6). Washington, DC: Office of Naval Research, Systems Research, April 1951.

Slocum, G. K., Hoffman, W. C., & Heard, J. L. Airborne sensor display requirements and approaches. Information Display, 1967, 4, 44-51.

Smith, A. A. Procedure for setting up radar scopes (DRML Technical Memo 163-9). Defence Research Board of Canada, 1956.

Smith, A. A., & Boyes, G. E. A neutral density filter for setting optimal bias on radar displays employing magnesium fluoride phosphors (DRML Report 163-12). Defence Research Board of Canada, 1957.

Smith, S. L. Display color coding for visual separability (Report MTS-10). Bedford, MA: MITRE Corporation, August 1963. (AD-462 872) (a)

Smith, S. L. Color-coded displays for data processing systems. Electro-Technology, April 1963, 63-69. (b)

Smith, S. L. Visual displays--large and small (Report ESD-TDR-62-339). Bedford, MA: MITRE Corporation, USAF Electronic Systems Division, Hanscom Field, MA, 1962. (AD-293 826)

Snadowsky, A. M., Rizy, E. F., & Elias, M. F. Misregistration in color additive displays (Report RADC-TDR-64-488). Griffiss Air Force Base, NY: Rome Air Development Center, 1964. (AD-610 528)

Snyder, H. L. Human visual performance and flat panel display image quality (Report HFL-80-1 ONR-80-1). Blacksburg, VA: Virginia Polytechnic Institute and State University, July 1980. (AD-A092685)

Snyder, H. L. A unitary measure of video system image quality. In D. B. Jones (Ed.), A collection of unclassified papers on target acquisition. Papers presented at Target Acquisition Symposium, Office of Naval Research, November 1972. (AD-758 022)

Synder, H. L., & Maddox, M. E. Information transfer from computer-generated dot-matrix displays (Report HFL-78-3/ARO-78-1). Blacksburg, VA: Virginia Polytechnic Institute and State University, October 1978. (AD-A063505)

Snyder, H. L, Greening, C. P., & Calhoun, R. L. An experimental comparison of TV and direct vision for low altitude target recognition (Report T-46/3111-4). Anaheim, CA: Autonetics, January 1964.

Snyder, H. L., Keesee, R. L., Beamon, W. S., & Aschenbach, J. R. Visual search and image quality: First interim technical report (Report AMRL-TR-73-114). Wright-Patterson Air Force Base, OH: Aerospace Medical Research Laboratory, 1973.

Sonn, M., & Carr, R. M. A comparative evaluation of P7 and P28 cathode-ray tubes for the detection and localization of sonar targets. Raytheon Corporation, Submarine Signal Division, November 1967.

Steedman, W. C., & Baker, C. A. Target size and visual recognition (Report WADD-TR-60-93). Wright-Patterson Air Force Base, OH: Wright Air Development Division, February 1960. (AD-235 129)

Stein, I. H. The effect of the active area on the legibility of dot-matrix displays. Proceedings of the Society for Information Displays, 1980, 21, 17-20.

Stephenson, S. D., & Schiffler, R. J. The relative legibility of five different segmented electroluminescent parts (Report RADC-TR-68-372). Griffiss Air Force Base, NY: Rome Air Development Center, September 1968.

Stevens, S. S. (Ed.). Handbook of Experimental Psychology. New York: John Wiley & Sons, 1951.

Swedish National Board of Occupational Safety and Health. Reading of display screens (Directive 136). 1 January 1979.

Sweet, A. L., & Bartlett, N. R. Visibility on cathode-ray tube screens: Signals on a P7 screen seen at different intervals after excitation. Journal of Optical Society of America, 1948, 38, 329-337.

Target Acquisition Working Group. Subject: Target acquisition definitions and acquisition by sensor (Working Paper, RAE/NWC). 9 August 1972.

Teichner, W. H. Predicting human performance. III. The detection of a simple visual signal as a function of time on watch (Report NMSU-ONR-TR-72-1). Las Cruces, NM: New Mexico State University, Department of Psychology, June 1972. (U148796)

Teichner, W. H., & Krebs, M. J. Laws of visual choice reaction time. Psychological Review, 1974, 81, 75-98.

Thornton, G. B. Detection time of radar pips under ideal operating conditions (Report No. 107-2). Toronto, Canada: Defence Research Medical Laboratories, December 1954. (AD-56406)

Tousey, R. Effect of cathode-ray tube screens on night vision (Report H-2226). Washington, DC: Naval Research Laboratory, January 1944.

Tyte, R., Wharf, J., & Ellis, B. Visual response times in high ambient illumination. Society of Information Displays Digest, 1975, 98-99.

Vanderkolk, R. J., Herman, J. A., & Hershberger, M. L. Dot matrix display symbology study (Report AFFDL-TR-75-75). Wright-Patterson Air Force Base, OH: Air Force Flight Dynamics Laboratory, 1975.

Vartabedian, A. G. Effects of parameters of symbol formation on legibility. Information Display, May 1970.

Vartabedian, A. G. Legibility of symbols on CRT displays. Applied Ergonomics, 1971, 2.3, 130-132.

Vaughan, W. S., Jr., & Kinney, J. A. S. Human engineering guides to design of displays for underwater applications (Contract N00014-79-C-0602). Annapolis, MD: Oceanautics, Inc., December 1981. (AD-A110317)

Vecht, A., Werring, N. J., Ellis, R., & Smith, P. J. F. Direct current electroluminescence in zinc sulfide: State of the art. Proceedings of the IEEE, 1973, 61, 902-907.

Wagner, D. W. Target acquisition with color versus black and white television (Report NWC TP-5800). China Lake, CA: Naval Weapons Center, October 1975.

Wald, G. Blue blindness in the normal fovea. Journal of the Optical Society of America, 1967, 57, 1289-1303.

Whitehurst, H. O. Ship recognition range on television. Effects of sun position, ship orientation and wake size (Report NWC TM-2964). China Lake, CA: Naval Weapons Center, October 1976.

Whitham, G. E. The determination of display screen size and resolution based on perceptual and information limitations. Information Display, July/August 1965, 15-19.

Whitmer, C. A. Peripheral form discrimination under dark-adaptation. Journal of General Psychology, 1933, 9, 405-419.

Williams, H. L., & Borda, D. J. Effect of selected parameters upon recognition of targets on a TV display (Report OR 6072). Orlando, FL: Martin-Marietta Aerospace Company, June 1964.

Williams, H. L., Borda, D. J., & Larue, M. A., Jr. Effect of selected parameters upon geographic orientation and target recognition on a TV display (Report OR 6336). Orlando, FL: Martin-Marietta Company, September 1965.

Williams, S. B. Visibility on cathode-ray tube screens: Viewing angle. Journal Optical Society of America, 1949, 9, 782-785. (AD-640 087) (a)

Williams, S. B. Visibility on radar scopes (Special Devices Report 166-1-82). Washington, DC: Office of Naval Research, 1949. (b)

Williams, S. B., & Hanes, R. M. Visibility on cathode-ray tube screens: Intensity and color of ambient illumination. Journal of Psychology, 1949, 27, 231-244.

Williams, S. B., & King, E. The effect of CRT bias on visibility of targets on a remote PPI (Special Devices Report 166-1-6). Office of Naval Research, Johns Hopkins University Psychology Laboratory, 1946.

Williams, S. B. et al. Operator efficiency as a function of scope size (Report RADC-TR-55-18). Griffiss Air Force Base, NY: Rome Air Development Center, 1955. (AD-614 04)

Wolf, E., & Zigler, M. J. Some relationships of glare and target perception (Report WADC-TR-59-394). Wright-Patterson Air Force Base, OH: Wright Air Development Center, September 1959. (AD-231 279)

Wolf Research and Development Inc. Data Display Programming (NASA-CR-1107). Author, September 1968.

Woodson, W. E., & Coburn, C. Recommended modifications to MIL-STD-1472B; selected section on controls, displays and related hardware. San Diego: Man Factors, Inc., May 1980. (AD-A091477)

Wyman, M. J., Rawlings, S. C., & Sturm, R. D. Laboratory studies of target recognition using terrain simulation. II. Effects of speed and field of view (Report T6-1762/3111). Anaheim, CA: Autonetics, August 1966.

Wyman, M. J. & Sturm, R. D. Laboratory studies in air-to-ground target recognition: XI. Preliminary evaluation of a dual TV system (Report T6-2833/501). Anaheim, CA: Autonetics, November 1966.

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